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THESIS

UNITARY JOINT STANDOFF CAPTIVE AIR TRAINING MISSILE AVIONICS DESIGN THROUGH OPERATIONAL CONCEPTS AND FUNCTIONAL REQUIREMENTS ANALYSIS

by

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March, 1996

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To accurately simulate the Unitary Joint Standoff (JSOW) weapon functions and provide pilots with the most realistic training, the captive air training missile (CATM) avionics design will fully implement well defined operational concepts and functional requirements in terms of flight simulation characteristics, operational functions, pilot feedback, and electronic interfaces. This would provide the Navy, Marines, and Air Force with a single, multi-capable, light weight CATM that consolidates CATM procurement, decreases aircraft turnaround time and increases aircrew training per flight hour.

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UNITARY JOINT STANDOFF CAPTIVE AIR TRAINING MISSILE AVIONICS DESIGN THROUGH OPERATIONAL CONCEPTS AND FUNCTIONAL REQUIREMENTS ANALYSIS

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

To accurately simulate the Unitary Joint Standoff (JSOW) weapon functions and provide pilots with the most realistic training, the captive air training missile (CATM) avionics design will fully implement well defined operational concepts and functional requirements in terms of flight simulation characteristics, operational functions, pilot feedback, and electronic interfaces. This would provide the Navy, Marines, and Air Force with a single, multi-capable, light weight CATM that consolidates CATM procurement, decreases aircraft turnaround time and increases aircrew training per flight hour.

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Secondly, my sincerest appreciation goes to Assistant Professor Isaac Kaminer and Professor Gerald Lindsey for leading the way down that path of knowledge. Professor Kaminer's avionics design class and project was the primary stimulus for my increased interest in control theory and SIMULINK simulations. His insights will continue motivate other students and contribute to the NPS Design Team. Professor Lindsey's abilities to present a problem in its simplest terms and from that systematically add complexities taught me how to disregard assumptions and develop sound concepts and solutions focused on the problems at hand.

Next, I wish to thank Mr. Larry Lefbom (PMA-201E4) and Mr. Kurt Reese (JSOW,China Lake) for involving and supporting the Naval Postgraduate School in their Unitary CATM research program.

I. INTRODUCTION

The Joint Standoff Weapon (JSOW) is an INS/GPS air-to-ground glide weapon that provides a standoff capability of 15 nautical miles (nm) at low altitude and 40 nm at high altitude against a variety of land and sea targets. The weapon will be delivered in three variants; Baseline, BLU-108, and Unitary, each of which will use a common weapon body and substitute various payloads.

The Naval Air Systems Command (NAVAIR) PMA 201 has signed a contract with Texas Instruments (TI) to develop a Captive Air Training Missile (CATM) for the Unitary variant. TI has prepared the Unitary CATM for the Concept For Operational Employment, Functional Requirements, and Warfighter reviews that began this Fiscal Year (FY96).

The Naval Postgraduate School Aeronautics Department has been contracted to provide a conceptual design of the Unitary CATM and is working closely with NAVAIR PMA 201E4, the JSOW Project Director, China Lake, and the TI JSOW Integrated Product Teams, Dallas. The NPS design team is organized as follows:

<u>Faculty</u>

Professor Gerald Lindsey	Team Leader/Structures
Professor Oscar Biblarz	Aerodynamics
Professor Conrad Newberr	System Integration
Assist Professor Issac Kaminer	Elect & Communications
Assist Professor Sandra Scrivener	Structural Dynamics

<u>Students</u>

CDR Dennis Reilly	Elect & Communications
CDR(S) David Wagner	Elect & Communications
LT Trent DeMoss	Structures
LT Brian Flaschbart	Training Function
LT Gary Formet	Training Function
LT Michael Scarry	Structures

This thesis includes four chapters that contribute to the NPS Design Teams endeavor to conceptualize the Unitary CATM. Since the weapon and internal CATM design and operational concepts are identical in many of the training phases, Unitary weapon documents were used as an information basis and amended to provide the most realistic simulations of pilot feedback, flight characteristics, electronics interfaces, and operational and maintenance functions. As such, much of this report is heavily dependent on several sources. The following paragraphs summerize the chapters of this thesis and the primary sources of information. The character 'X' holds the place for information that was not known at the time of this writing.

Chapter II is the NPS draft for the Concept for Operational Employment. This working copy has been forwarded to PMA201E4 for review and dissemination to the Warrior Product Team. This document was adapted from "Concept For Operational Employment Of The AGM-154 Joint Standoff Weapon System." Revision F.8. 26Apr95, "System Performance Document For The Joint Standoff Weapon (JSOW) Unitary Weapon System." Attachment(3). 26Jun95, <u>SLAM Technical Operators Reference Manual (STORM)</u>. 06Jun94, and short papers received from the various JSOW Teams.

Chapter III is the NPS draft for the Functional Requirements. This document was written in parallel with a more indepth functional study being conducted by LT Formet and will be incorporated by him into a single Functional Requirements Document. The report format follows the guidelines in DOD-5000.2M and the information sources are "System Performance Document For The Joint Standoff Weapon (JSOW) Unitary Weapon System." Attachment(3). 26Jun95 and the "Concept For Operational Employment Of The AGM-154 Joint Standoff Weapon System." Revision F.8. 26Apr95.

Chapter IV is a feasibility study to refocus the CATM design goal from a single weapon to a multi-weapon CATM to include JDAM, JASM, IMAV, and SLAM. Although not in the primary focus of the NPS Design Team tasking, a 'quick look' in the conceptual phase may reveal ideas that warrant PMA and industrial investigation. Information for component comparisons were obtained from Chapters IV and V above for the Unitary CATM, <u>SLAM Technical Operators Reference Manual (STORM)</u> 06Jun94 for the SLAM CATM and from <u>AGM-65F Navy IR MAVERICK</u> August 1991 for the IMAV CATM.

Chapter V discusses a simulation of an Unitary system using equations of motion, sensor modeling, Kalman filtering, and a feedback controller. It was developed by a AA4276 design group. The designers were CDR Dennis Reilly, CDR(S) David Wagner, LCDR Ray Collazo, and LT John Klein. The project will continue for the next two academic quarters when CDR(S) Wagner will present the complete simulation of a JSOW Unitary in flight with maximum lift-to-drag velocity control, waypoint 3-D navigation, and CATM to cockpit flight commands. If incorporated into the CATM, carriage pilots will receive simulated post weapon release navigation commands that will enable them to track the Unitary profile.

II. NAVAL POSTGRADUATE SCHOOL DRAFT FOR THE CONCEPT FOR OPERATIONAL EMPLOYMENT of the AGM-154 JOINT STANDOFF WEAPON (JSOW) UNITARY WEAPON SYSTEM CAPTIVE AIR TRAINING MISSILE (CATM) (working copy)

A. INTRODUCTION

The Joint Standoff Weapon (JSOW) Unitary Captive Air Training Missile (CATM) is currently in the XXXXX acquisition phase. A contract with Texas Instruments was signed on XX XXX XX to conduct the XXXXX phase of JSOW CATM development. JSOW Unitary CATM is preparing for Functional Requirement, Concept For Operational Employment, and Warfighter reviews beginning in Fiscal Year (FY) 1996.

This document outlines the concept for operational employment of the JSOW CATM by the organizational user. It is intended to familiarize the operational user with the JSOW Unitary CATM, but not as a source document for weapon requirements. General implementations and switchology reference the Navy F/A-18 C/D. Implementation in other aircraft will vary, depending upon aircraft and weapon station data bus structure and GPS capabilities. This document will be reviewed and updated periodically during the development process.

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B. GENERAL

1. Mission Need

JSOW CATM will provide the Navy, Marine Corps and Air Force with an effective air-to-surface weapon training capability which maximizes interoperability and affordability. There is a need for a CATM to effectively train aviators in simulated JSOW single plane and multiplane missions to include pre-mission planning, data transfer, weapon on deck and airborne checks, weapon function simulation prior to and post weapon launch, weapon navigation through target seeker turn on, target acquisition and terminal guidance. Furthermore, there is a need for a CATM to provide training for other weapons as well, such as JASM, JDAM, SLAM, and TBIP.

2. JSOW Weapon System and Target Sets Description

JSOW is an air-to-ground glide weapon that provides a standoff capability of 15 nautical miles (nm) at low altitude and 40 nm at high altitude against a variety of land and sea targets. The weapon will be delivered in several variants, each of which will use a common weapon body or 'truck' and substitute various payloads.

a. JSOW Baseline

The first version, JSOW Baseline, will dispense 145 BLU-97 combined effects munitions and is intended to attack the following types of <u>relatively soft targets</u>: fixed and relocatable air defense sites, parked aircraft, components of airfields and port facilities, command and control antennae, forward deployed weapon depots, stationary light vehicles, trucks and artillery and refinery components.

The Initial Operational Capability (IOC), defined as one squadron trained and certified ready for deployment with one shipfill of JSOW weapons, is planned for FY98.

b. JSOW/BLU-108

JSOW/BLU-108 utilizes six BLU-108/B sensor-fuzed submunitions, each of which contains four Skeet for a total of twenty-four warheads and is intended to attack the following types of mobile area targets: Massed land combat vehicle (LCV) threats including main battle tanks, wheeled or tracked armored personnel carriers (APCs) and light to heavy support vehicles (trucks). The primary target set is an armored column of LCVs on a road march commonly referred to as a representative armored formation (RAF). The IOC is planned for FY00.

c. JSOW Unitary

The JSOW Unitary variant will deliver the BLU-111, a 500 pound warhead derived from the Mk-80 series of weapons and will incorporate a post-release retargeting capability using the AN/AWW-13 data link and slewable seeker for terminal guidance. It is intended to attack the following types of point targets: energy production and industrial components, bridges, rail yards, small surface combatants and armed logistic ships.

Discussions in this document will emphasize the operational employment of the JSOW CATM vice the JSOW weapon, but at times will describe weapon methodology in order for the user to fully appreciate CATM simulation parameters.

3. Unitary CATM System Description

The JSOW Unitary CATM will IOC in FYXX and will exactly simulate the Unitary weapon capabilities and provide the pilot with the most realistic training possible. The CATM functions shall identically match the Unitary weapon in terms of pilot feedback, flight characteristics, electronics interface, operational and maintenance functions (except loading and arming procedures).

a. CATM Physical Characteristics

The CATM will consist of an aerodynamically efficient airframe without wings and tail surfaces and will be suspended by standard fourteen or thirty inch suspension lugs. The CATM size and weight will allow carriage on external stations and internal carriage in capable aircraft. The CATM will be stored in less space and loaded faster than the weapon as a fully assembled all-up round (AUR). The CATM length, width, height, are undetermined; however, the weight has a threshold of 500 pounds (objective of 200 pounds).

b. Mission Planning Support Systems

JSOW mission data will be downloaded from the Tactical Aircraft Mission Planning System (TAMPS) version 6.0 or the Air Force Mission Support System (AFMSS) to a Data Transfer Device (DTD) such as the Memory Unit (MU). The MU is then inserted into the aircraft and the information is passed to the CATM. Communication with the CATM will be via a data bus interface. Aircraft not capable of this interface will use equipment to load mission data directly into the CATM, then those aircraft will be capable of using the CATM in the same degraded modes as the Unitary weapon.

c. Simulated Flight and Attack Profile

After the simulated release from a launch platform, the CATM will provide steering, glide path, and velocity cues for the carriage aircraft all the way to the target by an integrated INS/GPS system, following the preselected elevation trajectory using either a direct flight path or a preplanned waypoint route to the target. Mission planning will specify the turn-on time or location for the seeker and data-link RF. The terminal dive angle is selectable to optimize the impact angle and weapon effectiveness and will not be simulated by the carriage aircraft. This will be programmable by the mission planner using TAMPS.

4. Training Mode Description

a. *Multiplane Mode*

If two aircraft are used during a CATM training flight, the carriage aircraft would typically perform all the prelaunch and launch operations, and then continue inbound to the target to simulate the missile free flight mission profile. The control aircraft, carrying a data link pod would have two choices: 1) simulate the postlaunch portion of a single aircraft tactical mission or 2) simulate the postlaunch portion of a two aircraft tactical mission. In the first case (simulating a single aircraft mission), the control aircraft would fly with the carriage aircraft during the prelaunch operations, turn outboard at the simulated release, become established within the control area at the required outbound flight conditions prior to seeker turn on, and perform JSOW postlaunch control. In the second case (simulating a two aircraft mission), the control aircraft would maneuver separately from the carry aircraft during the prelaunch operations, become established within the control area at he required outbound flight conditions prior to seeker turn on, and perform JSOW postlaunch control.

b. *Single Plane Mode*

If a single aircraft is used during a CATM training flight, the carriage/control aircraft ***must*** carry both a CATM and a data link pod, perform all the prelaunch and launch operations, and then continue inbound to the target to simulate the missile free flight mission profile. After seeker turn on, the single aircraft must perform postlaunch control as it continues towards the target with the CATM. The unrealistic part of this type of training mission is that postlaunch control takes place with the control aircraft inbound to the target and in close proximity to the CATM. In the case of a single aircraft tactical mission, the aircraft would typically turn outbound immediately after launch and the

missile would be separating at a high rate of speed during postlaunch control. However, postlaunch controls and weapon/CATM video reception have been proven by SLAM to be nearly identical regardless of whether the aircraft is flying with the CATM or away from it, and thus, the only significant practice omitted in this case is the postlaunch maneuvering necessary to establish the required outbound flight conditions prior to seeker turn on.

C. MISSION DATA REQUIREMENTS

The JSOW CATM program was initiated prior to the integration of GPS on all Navy launch platforms. Current projections by McDonnell Douglas (F/A-18, F-15E, and AV-8B), Northrop Grumman (F-14D), Lockheed Martin (F-16C/D and F-117) and Rockwell (B-1B) indicate that all JSOW capable aircraft will be GPS integrated by FY00 to FY02. However, an important difference in JSOW Unitary CATM capabilities will be the GPS antenna location on the carriage aircraft and the amount of satellite blockage from aircraft structures. A GPS antenna RF feature that allows the CATM GPS to receive signals from the aircraft's GPS antenna is a possible solution. However, coupling between the CATM's GPS and it's navigation computer may change from 'tight' to 'loose'. This effect on CATM performance should be investigated. As such, the CATM should not require GPS support from the aircraft except for data originating from mission planning and transferred via a data transfer device.

The CATM requires two categories of information to operate in other than a degraded mode: precise target location in the World Geodetic Survey of 1984 (WGS-84) datum and GPS data (almanac, satellite configuration and anti-spoofing status (AS/SV), time, and crypto key).

1. Target Location

Target coordinates must be defined by latitude, longitude and elevation in the WGS-84 datum. Information from other datums must be first converted to WGS-84 by the mission planning system or the aircraft. The CATM will incorporate into the target information a "terminal waypoint", as well as a terminal dive angle and altitude, which can be defined by the mission planner. This waypoint and terminal parameters will be used to set up the run-in heading and required distance to the target to optimize the data-link axis. If the planner does not specify a distance for this terminal leg, the CATM will calculate a minimum distance to account for turn radius and the specified attack conditions.

2. GPS Data

Standard GPS navigational signals are continuously available throughout the world from a specifically designed satellite constellation to anyone with a GPS receiver. Accuracies from the basic signal, known as the "C/A" code, are unacceptable for precision targeting. Precise positioning data is obtained through decryption of the coded signal sent along with the basic navigational information, known as the "P(Y)" code.

Satellite orbits are precisely tracked to allow estimation of receiver position as a function of time. GPS receivers determine the distance and rates of change of distances to each satellite at any given instant and combine this with known satellite positions to obtain an accurate fix. For rapid acquisition and targeting precision, GPS almanac, time of day, satellite configuration, anti-spoofing status and crypto key data must be passed to the CATM, or sufficient time allowed prior to release for the CATM to acquire and track at least one satellite vehicle (SV). If any of this information is missing, outdated, or corrupted, navigation accuracy and short range tactical training capability can be degraded.

a. *Almanac*

The GPS navigation system is based on a constellation of 24 satellites in low earth orbit. Almanac data tells the GPS receiver the location and health of the satellites in the celestial sphere; without this data the GPS system in the CATM will not function. Almanac data will be acquired from TAMPS or from a GPS equipped aircraft. Almanac data less than 3.5 days old for the entire constellation is required.

b. *Time of Day*

Time of Day (TOD) information is critical for the rapid acquisition of satellite information during the pre- and post-launch phases. TOD enables the weapon to access stored almanac data, determine which satellites are available and which code sequence to look for. TOD is typically automatically stored in the aircraft mission computer, but can also be updated by the pilot during preflight or passed to the CATM via a time mark block from the aircraft GPS receiver. (In the case of a non-1553 aircraft, time will be input as a power-up time during mission planning. In this case the CATM must be powered up within 10 minutes of the pre-determined time to maintain accuracy.) Inaccurate TOD data will result in prolonged searching by the CATM for usable satellite information with possible negative training results in short range launch simulation. Time of day is updated and synchronized to the GPS system when the first SV is acquired.

c. *Crypto Key*

The GPS crypto key, defined as the Crypto Variable Weekly (CVw), is required to make effective use of the potential accuracy afforded by the GPS system when Selective Availability (SA) is enabled. SA degrades position accuracy by varying the navigation signal, yielding a significantly larger location ellipse ("bubble") of uncertainty. The crypto key allows the weapon to access encoded data, the P(Y) code,

in the navigational broadcast to apply the appropriate correction for SA. This encoded data allows greater accuracy throughout the CATM's flight profile. Lack of or loss of the crypto key will result in the loss of satellite acquisition training and slightly less accurate aircraft course commands. Crypto key data will be loaded by the TAMPS onto the DTD and transferred via the aircraft or the mission data loader to the CATM.

d. Ephemeris

Each satellite has minor variations in its orbit. Ephemeris data updates the gross information provided by the almanac to allow precise determination of each satellite's position. This information can be acquired from a GPS equipped aircraft directly or from each satellite. In the case of GPS equipped aircraft, current ephemeris data, in no case over four hours old at the time of simulated weapon launch, will enhance the CATM acquisition speed and capability to better simulate the real missile. The CATM may obtain the ephemeris data from the launch platform GPS receiver or acquire the "C/A" code from a satellite. Reading the data from the satellite will add approximately 30 seconds to the time required for the first precision navigation solution. Ephemeris data can only be retrieved from satellite vehicles that are currently in view of the receiver.

e. Time Mark Pulse (TMP)

The time mark pulse allows multiple GPS receivers to be synchronized, thereby reducing the time required for a receiver to locate the appropriate satellites. The carriage vehicle may provide the time mark to the CATM receiver via the -1553 data bus. Lacking a time mark, the CATM must use the TOD information, which may result in longer search times with possible degraded accuracy for shorter range shots.

f. GPS Constellation Anti-Spoofing/Selective Availability (AS/SA) Configuration

Constellation AS/SA configuration status is to be provided by mission planning system and may not be transferred from the aircraft's GPS system. This information is the 4-bit AS status and configuration code for all SV's.

D. JSOW CATM STRIKE PLANNING

1. Strike Planning

Specific JSOW planning tools required to support the planning phase include charts showing pattern footprint, gross kinematic envelopes for various delivery altitudes and airspeeds and Joint Munitions Effectiveness Manual (JMEM) lethality models against various targets. These preplanned envelopes and terminal area maneuvers will be processed by the CATM's GPS/navigation computers and be displayed to the pilot as launch acceptability regions for simulated releases and as navigation flight commands for post release weapon flight profile simulations.

Several JSOW CATM targets can be planned using the same launch aircraft by moving the TAMPS cursor to another aimpoint, designating another JSOW TARGET and repeating the iteration described. The mission may be copied and the target and waypoints edited to expedite the process. Up to six separate targets can be designated for each CATM (CATMs are capable of storing up to eight missions; however, two missions are reserved for the self-targeting training mode). Each target can have its own CATM simulated launch point, waypoints, and final attack heading. Each LAR is displayed as the target is designated.

The time of the weapon impact is critical in training for coordination with other elements of the strike. CATM time-on-target and seeker turn-on time are required to predict when the control aircraft must be in position to receive the

data-link signal with sufficient time for the pilot to concentrate on target acquisition and aimpoint refinement. Weapon time-of-flight is therefore critical in defining the weapon launch time and location. By varying the winds in the planning process, the mission planner can observe their effect on strike timing and aircraft exposure.

E. PRODUCTS OF MISSION PLANNING

When TAMPS/AFMSS mission planning is complete, the planner needs everything required to execute his mission to be provided rapidly and easily. TAMPS provides kneeboard cards, strip charts and a loaded MU for the pilot to take to the aircraft. The MU will be loaded with aircraft mission data, JSOW mission data, GPS almanac and other information as described.

1. Data Transfer

After the mission is planned on TAMPS, the JSOW route of flight, target, GPS almanac, SV/AS, and CVw must be transferred to the CATM. Bulk data transfer may be accomplished using a DTD such as the AN/ASQ-194 Memory Unit (MU). (Note: When loaded with the CVw, the DTDs are classified as CRYPTO CONFIDENTIAL.) The MU will be inserted in a Memory Unit Receptacle (MUR) attached to TAMPS and loaded with JSOW route of flight, target, GPS almanac and other mission data. The crypto-classified MU is then taken to the aircraft and inserted in the aircraft's MUR. Once power has been applied and initial BIT has been performed, the aircraft detects the presence of the bulk data on the MU and loads it into the aircraft computers and via the -1553 data bus into the CATM. (When the aircraft is on the ground, a weight-on-wheels interlock inhibits the transfer of the CVw into the missile.) The pilot can monitor the progress of the BIT and data transfer but no direct action is required.

For non-1760 aircraft, or when the data cannot be loaded via the aircraft due to malfunction, the MU is placed in the data loader which is connected to the CATM via the normal -1760 data interface. The data loader conducts CATM BIT and transfers the necessary data to the weapon.

If data cannot be loaded in either of the above methods, GPS crypto key, target coordinates, SV/AS, and route data can be manually entered into a GPS equipped MIL-STD-1553 aircraft via the DDI. No provision currently exists for manual backup on aircraft without -1553 or GPS.

The following figure compares data transfer bus and GPS capabilities to the carriage aircraft configuration projected for FY00.

Table 2.1. Aircraft Model and Data Bus/GPS Comparisons

AIRCRAFT MODEL AND DATA BUS/GPS COMPARISONS					
	1553 w/o GPS	1553 w/ GPS w/oTMP, RF	1760 w/o GPS	1760 w/ GPS, TMP w/o RF	1760 w/ GPS TMP RF
F/A-18 A/B	<LOT 10				
F/A-18 C/D	<LOT 12		>LOT 12	L 12-18	?
F/A-18 E/F				X	?
F-14 D					X
F-15 E				X	
F-16 C/D				w/o TMP	
F-117				X	
AV-8 B				X	
B-1 B				X	

F. CATM LOAD AND GROUND CHECKS

Once aircraft and CATMs are assigned to a training mission, ordnance personnel will move each CATM from its shipping and storage container onto a standard bomb cradle and deliver it to the flight deck or loading area. No assembly or checkout functions are required prior to mating the CATM to the aircraft. After the CATM is suspended, ordnance personnel will perform the BIT function using aircraft power, to verify that the CATM is operational. 115V, 400Hz, 3 phase and 28V DC1 power in accordance with MIL-STD-1760 is required to perform BIT.

Although it is usually appropriate to replace a CATM that has failed BIT, the interface with the aircraft will allow ground and aircrews to assess the nature of the failure and to determine the level of degradation relative to the intended mission. This will enable crews to continue loading if the failure does not involve a critical function, minimizing excess ordnance handling and launch delays.

1. -1553 Aircraft Pre-launch

Prior to launch all mission data is loaded into the aircraft, verified and passed to the CATM. (If for any reason TAMPS or a MU is unavailable, mission data may be loaded into the CATM manually using the F/A-18 up-front control panel or its equivalent on other -1553 aircraft.) All CATM initialization, BIT and data load is automatic; the pilot is advised of CATM status via the BIT data page and JSOW display. Default weapon selections are made if they are not stipulated in the bulk data load from the MU.

2. Non-1553/1760 Aircraft Pre-launch

The CATM mission data, GPS almanac and GPS crypto key are loaded into a data loader, verified and passed to the CATM. Time of day for CATM power-up is also passed to the CATM via the data loader. This data will be stored in the missile Guidance and Control board Electronically Erasable Programmable Read Only Memory (EEPROM). No provision exists to load mission data in the case of data loader failure.

G. ENROUTE

Enroute to the target, the pilot may BIT the CATM again (IBIT) and review or edit mission parameters via the HSI. This will require the CATM to reinitialize after completing IBIT, and restart the transfer alignment and GPS acquisition processes. (The oscillator heater will remain powered during IBIT, so the 10 minute warm-up time is not required.) When power is applied to the CATM, with weight off wheels, the GPS

CVw is downloaded to the CATM automatically. For -1760 aircraft, power should be applied to the CATM at least 10 minutes prior to simulated release to allow GPS heater stabilization, but generally not more than 1 hour prior to planned TOT if operating in high thermal loading conditions to prevent the possibility of overheating the Guidance Electronics Unit. Maximum robustness in the presence of GPS jamming is achieved when the missile has at least one satellite in view and has acquired the P(Y) code from at least one satellite prior to release. If the carriage aircraft is equipped with a GPS receiver and has acquired P(Y) code prior to entering the jamming environment, then the CATM anti-jamming capability can be significantly enhanced through data transfer.

1. CATM GPS Initialization

Unlike some first generation GPS-equipped weapons, JSOW does not require a "canned" initialization maneuver or a fixed initialization point when operating on a -1553/1760 aircraft. The CATM will utilize the transfer alignment location information being passed from the carriage aircraft to inventory the almanac, determine the SV constellation status and acquire satellites. Nor does JSOW require a constant speed/altitude/heading profile while acquiring SVs; in fact, some maneuvering during acquisition will usually accelerate the process. The CATM will provide the aircrew with a transfer alignment quality status, GPS acquisition status and GPS jamming indication (if applicable).

The ability of the CATM GPS to acquire and track the GPS constellation is based on the data bus and GPS capabilities and the carriage location on the carriage platform. In cases when the CATM does not acquire GPS or loses GPS due to jamming or masking, the CATM will simulate navigation on it's own INS using information from the aircraft navigation system obtained during the transfer alignment or the last obtained GPS

information, respectively. Some degradation of performance may result until GPS is reacquired. This applies for pre and post release simulations.

H. LAUNCH ACCEPTABILITY REGIONS for SIMULATION

1. LAR Description

A launch acceptability region (LAR) is the three dimensional area in space inwhere the Unitary weapon may be released to attack a selected target. The CATM will utilize the its computer to compute the LAR information and send a two dimensional footprint to the carriage aircraft (-1553 only) for display as a ground overlay to the pilot. This will simplify the simulated release decision process and provide a greater degree of situational awareness, while helping to reduce overall pilot workload.

The LAR information will be displayed to show the kinetic range of the Unitary weapon (including a small maneuvering margin) under current flight conditions and will be continuously adjusted for variations in airspeed, altitude, heading and wind. Time-of-flight (TOF) is computed by the CATM and displayed to the pilot as a time-on-target (TOT) to aid in target deconfliction during coordinated strikes. The LAR does not provide any indication of the weapon's vertical flight path; therefore, terrain should be considered carefully prior to simulating the post launch flight path of the Unitary weapon. There are Four Types of LAR's:

a. In-Range LAR (IRLAR)

The dynamic IRLAR is the area in which the Unitary weapon is capable of flying directly to the target, bypassing all pre-planned waypoints and having sufficient energy available to execute the terminal maneuver. The IRLAR is displayed as a circle, or an arc at longer ranges or larger scales, centered about the target.

b. In-Zone LAR (IZLAR)

The dynamic IZLAR is the area in which the Unitary weapon has the energy to fly to all pre-planned waypoints and to execute the terminal maneuver. The IZLAR is displayed as a sector relative to the first pre-planned waypoint and current aircraft heading.

c. Pre-Planned In-Zone LAR (PP-IZLAR)

The PP-IZLAR is an optional display based on mission planning data only. The PP-IZLAR may be displayed as a geographically stabilized sector positioned relative to the first pre-planned waypoint and is shown as a series of dashed lines to differentiate it from the dynamic IZLAR. The PP-IZLAR is provided for information only and does not change with current flight conditions. A line segment extends out of the PP-IZLAR launch point (displayed as a pentagon) indicating the pre-planned launch course. The PP-IZLAR and associated information may be removed by the pilot using the declutter selection.

d. Minimum Range LAR (MRLAR)

While not a unique LAR display, the MRLAR identifies the minimum range at which JSOW will implement the IRLAR rules.

2. LAR Operation

There are five phases of LAR display that a pilot may encounter during employment of JSOW. In each, if the pilot has not overridden the terminal bearing feature, the CATM will use it in its calculations. It also is important for the pilot to remember that dynamic LAR's are dependent upon actual flight conditions and may change drastically as the aircraft is maneuvered.

a. Outside the IRLAR

When the aircraft is enroute, the pilot will first observe a predictive mark on a line between the aircraft and the target which shows where the boundary of the IRLAR would

be if the aircraft made an instantaneous turn towards the target while maintaining current flight conditions. As range decreases, or the display range is expanded, the IRLAR display will appear. The IRLAR will reflect enroute flight conditions and may change in size as the aircraft maneuvers towards the target or launch point. The pilot is cautioned that simulated release is not inhibited outside the IRLAR.

b. Inside the IRLAR, Outside the IZLAR

When launch simulation is inside the IRLAR but outside the IZLAR, the CATM will give steering directly to the target utilizing the terminal waypoint. It will not attempt a midcourse intercept of the pre-planned route.

Once the aircraft has entered the IRLAR, a dynamic IZLAR will be displayed. If the flight conditions are near those estimated during mission planning, the dynamic IZLAR should approximate the PP-IZLAR. Similar to the predictive mark for the IRLAR, a mark will be displayed on a line towards the first pre-planned waypoint showing the outer boundary of the IZLAR if the aircraft were to instantaneously turn towards the first waypoint while maintaining all other flight conditions. The IZLAR will displace about the launch point to cue the pilot that maneuvering to pre-planned parameters is required in order to match the planned and dynamic LARs, although this is not required.

Both a pre-planned TOT and a straight-line TOT will be computed and displayed to the pilot. The straight-line TOT will be based on a dynamically computed TOF, while the pre-planned TOT will be based on the pre-planned TOF. This will allow the pilot to make corrections to airspeed/altitude and maneuver to adjust pre-planned TOT for coordinated strikes.

c. Inside the IZLAR

The pilot can simulate release from anywhere inside the IZLAR and JSOW will have sufficient energy to fly the entire pre-planned mission. The IZLAR will increase, decrease or disappear as altitude and/or airspeed are changed, or the carriage aircraft turns toward or away from the pre-planned launch point. TOT estimates are constantly computed by the CATM based on dynamic TOF estimates.

d. Flown Past the IZLAR

If the aircraft flies beyond the IZLAR, where JSOW is no longer able to fly through the first pre-planned waypoint, the IZLAR will be displayed aft of the aircraft's position. The aircraft will still be in the IRLAR and a direct route launch is still permitted.

To utilize the planned route, the IZLAR should be reentered. The inherent maneuverability of the JSOW will, however, also allow it to attack targets behind the wing line of the launch aircraft. This capability will enable the pilot to simulate an attack on a target which he has flown beyond, by launching from anywhere within the IRLAR, regardless of relative location or heading. If the IRLAR is removed, or the aircraft is outside the arc, it is an indication from the CATM that JSOW does not have sufficient energy to reach the target and execute the terminal maneuver.

3. Environmental Effects on LARs

Some of the challenges of employing standoff glide weapons are winds, altitude, air temperature and humidity that may significantly limit range. Winds should be entered for every leg of the JSOW route of flight (if these can be predicted) to improve fidelity of the LAR information with CATM range simulation. Air temperature and humidity are used in mission planning to more accurately define the range.

4. Terminal Maneuvering Effects on LARs

JSOW has the capability to adapt terminal dive angles to improve weapon impact angles within a limited range using the target option selections. This adaptation has a minor impact on LAR size. The 'hard' target selection will be most restrictive, requiring the greatest maneuvering energy reserve.

I. SIMULATED RELEASE AND TARGET ATTACK

1. Carriage Aircraft

Following the simulated JSOW launch, the primary mission of the CATM carriage aircraft is to follow as closely as possible: 1) a groundtrack profile which simulates missile free flight groundtrack of the selected JSOW training mission, 2) altitude profile which follows the training mission missile free-flight altitude profile, and 3) missile freeflight groundspeeds. The carriage aircraft may also perform postlaunch control if a separate control has not been designated for that task.

The seeker is activated at the range to the target specified in the mission plan and commanded to point at the target by the CATM navigation system. The CATM transmits the video image of the target scene via data link to the control aircraft. Following the control aircraft commanded lock-on, the CATM seeker tracks the designated target until target flyby.

2. Control Aircraft

Following the simulated JSOW launch, the control aircraft procedures for CATM control are identical to the corresponding control procedures for the tactical JSOW postlaunch control. CATM control includes selection of seeker tracking options, identification of the intended target, seeker slew, target lock-on, and monitoring of target tracking until target fly-by.

The aircrew monitors the seeker video transmitted by the CATM to locate the target. The aircrew may designate seeker field of view, hot or cold track, and target centroid or track mode. After the target is identified, the aircrew slews the seeker tracking gate over the desired target trackpoint, commands target track, monitors target tracking status, and if required, inputs target track command updates.

3. JSOW CATM Simulates Both Attack Modes

a. Pre-Planned (PP)

PP is the primary delivery mode for JSOW. This mode can be employed when the exact geodetic coordinates of the target are known prior to simulated weapon release. PP utilizes the full mission planning capability described above and maximizes employment effectiveness in most environments. TAMPS or AFMSS mission data is inserted into the CATM, the pilot flies the aircraft to the IRLAR or IZLAR and simulates release. The CATM will navigate and provide pilot commands to the target using GPS-aided inertial navigation, and command the preplanned attack maneuver.

A subset of this type of mission involves 'Third Party Targeting'. New or modified information may be received by the aircraft prior to takeoff or while enroute to the launch point via data-link, clear or secure voice. The pilot can enter these new route or target coordinates, designate them a JSOW target and pass them to the CATM prior to simulated release. If route of flight target coordinates are passed by a third party, the pilot must be aware that the CATM provides no reasonability check for errors. If a route is in excess of the kinematic range of the real weapon at current flight conditions, no LAR will be displayed. It is possible in this case that the error might not be detected until approaching the anticipated IRLAR.

b. *Self-Targeting (ST)*

Current delivery aircraft sensors were not designed with full JSOW capabilities in mind, simply because no existing air-to-ground weapons either require or can make use of precise target coordinates at long ranges from the target. Traditional weapons, released at much shorter ranges, distant target acquisition and location were used only for cuing and identification, not for targeting. With the advent of the JSOW capability, aircraft targeting sensors will be upgraded eventually to match the weapon kinematics and the threat.

The ST mode is available to the pilot when no pre-planned target data is available prior to reaching the target area and the target must be acquired using on-board sensors. In the ST mode the pilot places the appropriate sensor on a target, designates the target with the CATM selected and the aircraft computer interpolates the sensor positioning and sends the coordinates to the CATM. In this case the CATM will navigate directly to the target, or if the pilot has time to enter a terminal attack heading, he may do so and the CATM will navigate to the terminal waypoint using the default terminal range.

The maneuverability of the Unitary weapon will allow a pilot to designate a target with the CATM at extremely short ranges, fly past the target and simulate launch. However, aircraft maneuvering required to simulate the weapon flight path as it turns toward the target may be impracticable or even unsafe depending on surrounding terrain and the aircraft flight regime.

The aircraft may estimate a target location for moving targets based on existing target speed and direction. If this position estimate is coupled with a pilot visual cue on the heads up display (HUD), then aircraft flight path adjustments or delays can be made to provide a more favorable attack.

Although the JSOW ST mode is less accurate and thus less desirable than the PP mode against fixed targets, it still offers a more favorable standoff range than is achievable with close-in, direct fire ordnance. Aircraft not equipped with a GPS receiver will have to consider a lengthier simulated weapon time of flight for satellite reacquisition and target identification and lock on.

c. Offset Aimpoints. NEEDS UPDATE, MAY NOT BE CORRECT

An offset aimpoint allows a pilot to attack a target that is not readily discernible on aircraft sensors. When using an offset, the pilot will designate an alternate feature or object whose spatial relationship to the target is accurately known and which is significant to the sensor of choice. The carriage aircraft system must then interpolate the target coordinates obtained from the sensor cursor/reticle location and apply the desired offset information. These computed coordinates are then passed to the CATM as the desired target.

The CATM will only utilize target coordinates and will not calculate an offset from any point. The ability to use offset aimpoints, and the accuracy with which a target may be attacked using an offset aimpoint, is dependent on the carriage aircraft's sensor and system accuracy.

4. Target Overflight

Upon target fly-by (as indicated by the seeker reaching its lower lookdown position followed by target break-lock) the CATM should be immediately deselected by the carriage aircraft prior to initiating carriage aircraft maneuvers to avoid possible seeker damage.

5. Time on Target (-1553 AIRCRAFT)

The CATM will compute time-of-flight to the target based on current flight simulation and wind conditions. The CATM will send computed TOF at sufficient update rates to let the

carriage aircraft compute weapon time-on-target for display to the pilot.

When the aircraft is outside of the IRLAR, the displayed time-on-target is based on the current time-of-day plus estimated time to the pre-planned launch point plus pre-planned time-of-flight. Once the aircraft has penetrated the IRLAR, the time will be based on a direct flight to the target (or terminal waypoint if so planned). When the aircraft enters the IZLAR, the time of flight will be computed as the time required to fly through all pre-planned waypoints.

J. CATM TRAINING TIMELINE

The following timelines are based on the best available information, however modifications may occur as hardware integration and testing continue. Unless indicated, times shown represent maximum durations. (All times are mm+ss.ss)

1. General Sequence: Mil-Std-1553/1760 F/A-18

a. Mission Planning

t=00+00	o Start detailed JSOW training mission planning
t+40+00	o Finish detailed mission planning (assumes 4 targets,10 minutes per route,8 waypoints,1 waypoint edited,meteorological data base accessed once, target data base accessed once, relevant order of battle is displayed prior to starting,and no radar terrain masking displays requested)
	o Return/start aircraft route planning
t+90+00	o Finish aircraft route planning
	o Initiate hardcopy generation (kneeboard, stripchart, etc.)
	o Initiate MU data download
t+91+00	o MU dataload complete
t+95+00	o Hardcopy generation complete

b. CATM Upload

t+00+00 o CATM staged on bomb trucks at aircraft

t+10+00 o CATM upload complete

c. BIT And Mission Data Download

o Pilot inserts MU into launch aircraft

o Power applied to launch aircraft

t=00+00 o SMS powers up,store inventory conducted

o Power up BIT performed automatically

o Aircraft applies 115 VAC/400 Hz/3 Phase power to pass BIT

o Aircraft applies 28 VDC1 to CATM GPS oscillators

t+00+08 o Pilot selects CATM, status query begins

t+00+13 o CATM status displayed on SMS

t+00+17 o Pilot commands BIT (IBIT)

t+00+37 o IBIT completed

-Pass BIT, CATM ready status reported

-If failed a critical BIT, initialization discontinues,all power is removed and store initialization is discontinued. CATM Fail reported to the pilot

-If failed a non-critical BIT, "CATM degraded" message sent to pilot. Pilot can access degradation code on cockpit displays

t+00+47 o Begin MU download to the CATM and a/c mission computers

-mission and GPS data loaded into EEPROM

-CVw loaded into PPS-SM RAM

t+00+51 o MU download completed

t+00+55 o Aircraft verifies download status

t+01+00 o Aircraft displays BIT status

o GPS keys zeroized from PPS-SM

o 115 VAC power removed from CATM when

o GPS keys zeroized from PPS-SM

o 115 VAC power removed from CATM when deselected

o 28 VDC1 power remains on CATM for GPS heater

d. Enroute Sequence

t=00+00 o Pilot selects CATM on the SMS

o 115V Power applied to CATM without critical BIT failure

o 28V applied to GPS oscillator

t+00+00.25 o Tactical code downloaded from EEPROM

t+00+00.50 o MIL-STD-1553 initialized

t+00+05.10 o IMU ready

t+00+10 o Periodic BIT (automatic, occurs every 10 seconds)

t+03+00 o Transfer alignment acceptable (upper limit) (transfer alignment continues automatically)

o GPS keys downloaded from aircraft mission computer

o Time is acquired and ephemeris data received

t+08+00 o GPS supports C/A code acquisition in the CATM

-8+00 after 28 VDC1 applied -OR-

-3+00 after CATM selected -whichever is LAST-

t+10+00 o GPS warm-up complete, P(Y) code acquisition available

-10+00 after 28 VDC1 applied -OR-

-3+00 after CATM selected -whichever is LAST-

o Pilot selects mission

o Pilot checks air-to-ground "ready"

o Pilot flies into IZLAR to simulated release point

e. ***Simulated Release Sequence For Normal Release Within IZlAR***

t=00+00 o Pilot simulates launch

t+00+00.20 o Carriage aircraft sends release consent signal

t+00+20.05 o State 5 GPS acquisition (nominal)

-if TMP or 1 SV tracked before release from -1760 aircraft

t+00+25.05 o GPS ionospheric correction complete

t+00+27.05 o Navigation solution converge/GPS aided navigation begins

f. ***Endgame Sequence***

t-00+36.04 o CATM seeker begins video generation (nominal turn-on time)

t-00+34.04 o CATM initiates video datalink transmission

t-00+32.04 o Video normalization complete

t-00+30.04 o Pod video datalink locked

t-00+28.04 o Control pilot 'heads down', begin context object acquisition (3nm)

t-00+18.14 o Control pilot designates context object, go 'heads up'

t-00+16.03 o Control pilot 'heads down', begin target object detection

t-00+12.00 o Designate target, go 'heads up'

t-00+11.87 o Target tracked

t-00+09.80 o Control pilot 'heads down', refine aimpoint if required

t-00+02.00 o Aimpoint refinement lockout

t-00+00.12 o Seeker blind range

t-00+11.87 o Target tracked

t-00+09.80 o Control pilot 'heads down', refine aimpoint if required

t-00+02.00 o Aimpoint refinement lockout

t-00+00.12 o Seeker blind range

o Carriage pilot deselects CATM

g. *Post-Mission/landing*

o Mission data cleared/MU GPS Keys (CVw) zeroized from DSU on pilot command during return flight or automatically after weight-on-wheels. (MU is now declassified.)

o Mission data in EEPROM command cleared in CATM by aircraft mission computer, code processing algorithm remains in CATM EEPROM.

o MU is removed during postflight inspection by pilot.

2. Abridged Sequence For non-MIL-STD-1553 Aircraft

a. *Mission Planning (See timeline for Mil-STD-1553/1760 Aircraft)*

o The JSOW Mission planning is completed using TAMPS version 6.05 or higher.

o GPS keys are attached to the JSOW mission package file, including CATM power on time, location, attitude, velocity and heading; and simulated launch location, attitude, velocity and heading.

o Key Index File (KIF). The JSOW Mission Package is downloaded onto a Digital Data Set (DDS), the AN/ASQ-215.

o The pilot creates an F/A-18 mission data package and down loads it to the MU.

b. *Bit/Mission Data Download*

o The pilot retrieves the DDS and MU from TAMPS and proceeds to the aircraft for preflight.

The pilot provides the DDS with the JSOW mission package to the authorized ordnance personnel.

o The ordnance personnel connect the CMBRE to the JSOW CATM via the MIL-STD-1760 Umbilical and inserts the DDS in the CATM and the information is stored in the CATM guidance and control board EEPROM.

o The CMBRE provides 28V DC1 and 115V 400Hz 3 phase power to the CATM and commands it to perform IBIT. If the CATM fails BIT, refer to proper loading checklist for troubleshooting.

o After successful completion of IBIT the JSOW mission data package with GPS keys is downloaded from the DDS to the CATM and stored in the CATM guidance and control board EEPROM.

o The pilot inserts the MU into the aircraft receptacle.

c. CATM Upload

o The ordnance personnel disconnect the CATM from the CMBRE and moves the CATM to the designated aircraft pylon for upload.

d. Enroute and Launch Procedures: (Preplanned BOC Only)

TBD

e. Simulated Release Sequence Within IZLAR

T B D

K. TRAINING

1. Human Systems Integration

A principal objective of the JSOW CATM is to reduce the total training burden of captive carry weapons on aircrews, ordnance and other personnel while increasing the training advantages of a fully functional light weight CATM (i.e., amount of training realistically conducted per flight hour).

To the maximum extent possible, training requirements for maintaining and employing the JSOW Unitary and the Unitary CATM variants will be the same.

2. Aircrew Training

Aircrew training will be conducted at all levels of the training pipeline from the fleet readiness squadron (FRS) to special readiness exercises such as Red Flag. JSOW Unitary will utilize a lightweight CATM equipped with a seeker and data-link to provide training for man-in-the-loop control. Aircraft simulators will be capable of providing realistic simulation of JSOW employment including cockpit display of JSOW symbology. No unique training facilities will be required.

a. F/A-18 OFP-11C

Complete training may be accomplished by carrying a JSOW CATM or limited training may be accomplished by carrying a captive JSOW. When the pilot selects the JSOW, the CATM/weapon will compute the LAR and will allow utilization of normal JSOW launch modes. The pilot can inhibit release by boxing SIM on the stores management system (SMS) page. TAMPS planned missions may be utilized for training, or the pilot may use the ST mode. In the captive carriage mode, there are no plans to simulate a post-release JSOW flyout by providing steering cues to the pilot.

b. F/A-18 OFP-13C and Later

In addition to the captive carriage capability, limited training for JSOW is available to the pilot at any time using a non-captive carriage training mode (SIM mode) contained in the aircraft mission computer hard code. The JSOW SIM mode is very similar to the air-to-air SIM.

The JSOW SIM mode enables all displays, cues and steering to be generated by the aircraft as if a JSOW were actually on board. These displays are shown whenever the pilot is in SIM mode, has selected JSOW and designates a JSOW

target by the means described above. Training may utilize TAMPS planned missions, although, TAMPS mission planning is not a prerequisite for entry into the training mode. Lacking TAMPS data the pilot may choose from a set of generic missions or simulate the ST mode. The aircraft mode uses a truncated algorithm which reflects the true displays of the JSOW weapon to approximately 95% fidelity. As in the captive carriage mode, there are no plans to simulate a post-release JSOW flyout by providing steering cues to the pilot.

The following table summarizes current (FY96) F/A-18 computer hardware and software compatibility.

Table 2.2. F/A-18 Hardware/Software Compatibility

F/A-18 HARDWARE/SOFTWARE COMPATIBILITY					
MODEL	A/B	C/D			
LOT	5-9	10-14	15-16	17	18 & up
COMPUT-ER	XN-5 CP1539A	XN-6 CP1699A	XN-8 CP2215	XN-8 CP2215	XN-8 CP2216
92A	X				
10A	IN WORK				
91C		X	X	X	X
09C			X	X	X
11C			X	X	X
13C					X
15C					X

3. TACTS/ACTS Integration

The CATM will be compatible with existing Tactical Aircraft Combat Training System (TACTS) ranges as will be both the captive carriage and software only training modes. The integration of the TACTS/ACTS F/A-18C/D JSOW training capability is being conducted in parallel with testing and development phases. JSOW will mark the first weapon to allow TACTS/ACTS training at IOC.

a. Mission Planning Support

It is anticipated that the OFP-13C SIM mode will include the ability to accept TAMPS JSOW mission data from the MU. If this is not implemented by the F/A-18, the data will need to be loaded manually. A means to load the bulk TAMPS data from several aircraft directly to the TACTS/ACTS range station is being investigated. The mission data which can be loaded will include the JSOW route of flight (up to eight waypoints), pre-planned release point, target or offset aimpoint, target identification and terminal approach bearing and leg length. This information will be used by TACTS for display generation, LAR development and post-launch flight simulation.

b. LARs

The TACTS/ACTS software will be modified to include the JSOW LAR algorithms. This will be used for real time and post-flight displays. The LARs will be derived from TACTS aircraft positioning data, JSOW delivery mode information and aircrew edited data downlinked to the ground station.

c. Attack Modes

(1) Pre-Planned Missions. The PP mode will be functional in the OFP-13C SIM mode and will include applicable controls and displays up to simulated release, but will not provide flight profile commands for the weapon flight path. The CATM will be fully functional during all simulated flight phases.

PP missions with third party targeting will be included in the TACTS/ACTS JSOW integration and will include post launch flight profile simulation on the ground. The PP mode in TACTS will allow for pre-programmed information, such as waypoints and target data, for up to six missions. Aircrew selected delivery mode, waypoint or SL, will be downlinked to the TACTS ground station for simulation and display.

(2) Self-Targeting Missions. The ST mission will be included in the OFP-13C SIM mode and will include applicable controls and displays up to simulated release. The ST mode with launch information for up to two targets will be included in the TACTS/ACTS simulation and will include post launch flight profile simulation. Aircrew selected delivery modes will be downlinked to the TACTS station for simulation and display.

d. Post-Launch Simulation

The TACTS/ACTS JSOW integration program will assume 100% post-launch JSOW navigational accuracy and consequently will not include GPS and INS system simulations. As such, the GPS satellite status, almanac, ephemeris and cryptographic system information/capability will not be required for the simulation. This is not considered unreasonable, since the training range event scheduling may allow planners no choice in TOT optimization for SV configuration.

e. Targets

The TACTS/ACTS JSOW integration program will use existing range targets only. Terminal waypoints and offset waypoints will be available only for association with existing targets.

f. CATM Video Viewing and Recording

Video should be viewed either directly through the CATM on the carriage aircraft or through the CATM via data link in the control aircraft. Video should be recorded by separate recorders in the CATM, data link pod, or the aircraft

internal recorder. Video on/off should be manual (pilot selectable) or automatic at data link/seeker head turn-on.

g. Maintenance Training

Training for ordnance and maintenance personnel in the handling and repair of JSOW and JSOW CATM will consist of classroom and "hands-on" training using airborne test/training missiles (ATM) and CATMs.

L. LOGISTICS AND SUPPORT

1. Maintenance Planning

Specific maintenance concepts will be identified in the Joint Integrated Logistic Support Plan (JILSP). However, it is intended that JSOW CATM maintenance will be performed at three levels for the Navy (organizational, intermediate and depot) and at two levels for the Air Force (organizational and depot).

a. Navy Organizational (O-level)

At the O-level, visual inspection, upload/download, data load and verification, crypto loading and BIT will be conducted.

b. Navy Intermediate (I-level)

I-level maintenance will consist of removing the CATM from containers for operational use and repackaging unserviceable units for transportation to the CATM depot, performing visual inspection, minor corrosion control and BIT.

c. Common Depot (D-level)

Depot level maintenance of the CATM will be at a common site to minimize duplication of resources between the services. D-level maintenance will be subdivided into AUR depot (AUR D-level) and component depot (CD-level). AUR D-level will be capable of performing functions specified for the I level, plus conducting system tests to isolate faults to specific components and replace faulty components. Additionally, the AUR D-level will install, test and replace

the test instrumentation kit. The CD-level will perform all maintenance beyond the capability of the AUR D-level including the repair of defective components.

d. Air Force Organizational

Air Force organizational level maintenance will be performed by AFSC 461X0 and 462X0. Air Force O-level maintenance consists of on-equipment, including upload/download and visual inspections, and off equipment (CATM and container) including visual inspections, minor corrosion control, upload/download to transport trailers and BIT.

2. Support Equipment

JSOW CATM will be compatible with existing munitions handling and loading equipment. The CATM will maximize testability using BIT and the Consolidated Automated Support System (CASS) interface unit. CASS test equipment will be the primary resource for AUR D-level and CD-level testing and system diagnostics.

III. NAVAL POSTGRADUATE SCHOOL DRAFT for the FUNCTIONAL REQUIREMENTS of the AGM-154 JOINT STANDOFF WEAPON (JSOW) UNITARY WEAPON SYSTEM CAPTIVE AIR TRAINING MISSILE (CATM) (working copy)

A. INTRODUCTION

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1. General Description of Operational Capability

The JSOW Unitary Weapon System is an advanced version of the AGM-154 JSOW Weapon System. The JSOW family of weapons is intended to be an affordable mix of weapons able to destroy a broad spectrum of surface targets, day or night and in marginal weather, from a launch position outside the target's point defenses.

The Unitary variant with its unitary warhead is intended to emphasize engagement of a diverse set of targets that are susceptible to blast and fragmentation kill mechanisms. The Unitary is a large, single target bomb which can be pre-programmed to fly to waypoints before performing its final run and is steerable by aerodynamic control surfaces (wings and tail). It has no independent propulsion system. The Unitary missile has a data link and can be flown by the pilot to reach its exact target. Its IR seeker returns image data to the cockpit for this purpose.

2. Mission Need

JSOW CATM will provide the Navy, Marine Corps and Air Force with an effective air-to-surface weapon training capability, which maximizes interoperability and affordability. There is a need for a CATM to effectively train Aviators in simulated JSOW single plane and multiplane missions to include pre-mission planning, data transfer, weapon on deck and airborne checks, weapon function simulation prior to and post weapon launch, weapon navigation through target seeker turn on, target acquisition and terminal guidance. Furthermore, there is a need for a CATM to provide training for other weapons, such as JASM, JDAM, SLAM, and TBIP.

B. THREAT

The JSOW Unitary Weapon System threat includes the threat to the AGM-154 system, as well as additional potential threats that may exist to the weapon seeker and the data link subsystems. Potential threats to the seeker and data link are described in the JSOW System Threat Assessment Report (STAR) and Strike and Air Warfare Intelligence Compendium (SAWIC). A JSOW Unitary Weapon System and Unitary CATM objective is to be fully functional in the countermeasures and counter-countermeasures environment defined in the STAR.

C. SHORTCOMINGS OF EXISTING SYSTEMS

1. Captive Carry

Training may be accomplished by carrying a captive JSOW, which is a major disadvantage a majority of the time. In the carrier environment, the weight difference between the CATM (threshold of 500 pounds and an objective of 200 pounds) and the Unitary weapon (threshold of 1965 pounds and an objective of 1065 pounds) has a tremendous impact on the amount of usable fuel an aircraft can land with. The more weight the

aircraft carries in stores, the less fuel it has available for recovery and the narrower the tank/BINGO margin. This implicates strict tanking and BINGO requirements and ultimately restricts ship maneuvering and recovery times.

Captive carry of the Unitary weapon for training purposes is unrealistic due to its high drag count, large weight, live payload, danger to ground personnel and the airframe from inadvertent wing spread, and reduced fatigue life. Most importantly, there are no plans to simulate a post-release JSOW flyout training feature by providing steering cues to the pilot.

2. Unitary Air Vehicle Converted to CATM

The Unitary Air Vehicle is too large to serve as a CATM vehicle. Removal of the explosive payload, control actuators, control surfaces and wings would still result in an overly burdensome vehicle. In addition, ballast (unnecessary weight) may have to be added for CATM center of gravity, vibrations and jettison restrictions.

3. Software Simulation

In addition to the captive carriage capability, limited training for JSOW Unitary is available to the pilot at any time using a non-captive carriage training mode (SIM mode) contained in the aircraft mission computers (F/A-18 OFP-13C and later). The JSOW SIM mode enables all displays, cues and steering up to the release point to be generated by the aircraft as if a JSOW were actually on board. As in the captive carriage mode, there are no plans to simulate a post-release JSOW flyout by providing steering cues to the pilot, nor can the seeker turn-on, lock-on, and terminal guidance be simulated since there is not a seeker head onboard.

4. Modification of any Existing CATM

The JSOW Unitary will incorporate the new IR scanning focal plane array technology onto a seeker head, which does not yet exist in any other family of airborne weapons. A CATM

of the same technological generation is not available for modification. CATMs of other IR weapons (IR MAV, SLAM, and TOMAHAWK TBIP) use a lower resolution gimbaled seeker head and have fundamental differences (weight, data link, programming capabilities, compiler language) too difficult to upgrade to JSOW. However, the reverse concept may be valid and the feasibility of combining JSOW and redesigned IR MAV, SLAM, and TOMAHAWK TBIP CATMs will be discussed later.

D. CAPABILITIES REQUIRED

Operational Flexibility. The JSOW Unitary Weapon System is intended to be a highly flexible weapon system that replaces a number of weapons currently deployed. It is important that the CATM can be effectively deployed under various operational conditions that might arise under realistic tasking scenarios. Flexibility must be available in mission planning, launch aircraft operations, control aircraft operations, and weapon operation. The system specification requirements must fully reflect the need for such versatility in the employment of the weapon. It is critical that real world implications be considered when generating requirements in this document and in making design decisions that will affect the operational utility of the weapon.

1. Weapon Mission/Operational Performance

The JSOW Unitary system shall be capable of both land and carrier based operations. The weapon system shall be capable of engaging and destroying a large variety of tactically significant land and sea targets that are vulnerable to blast and fragmentation kill mechanisms. Target emphasis shall be 1) critical components of energy production facilities, airfield complexes, industrial complexes, harbor facilities, and rail yards, 2) bridges, and 3) small surface combatants, and armed logistics ships. JSOW shall provide low and high altitude launch capability from outside target point defenses to

enhance tactical aircraft survivability and combat sustainability. The JSOW Unitary Weapon System shall be compatible with the JSOW Concept of Operation.

2. CATM Mission Performance

To accurately simulate the Unitary weapon capabilities and provide the pilot with the most realistic training, the CATM functions shall identically match the Unitary weapon in terms of pilot feedback, flight characteristics, electronic interfaces, operational and maintenance functions (except loading and arming procedures). The CATM shall be compatible with the following deployment conditions.

a. The CATM will be deployed on Navy, Marine Corps, and Air Force aircraft with non 1553/1760, -1553, and -1760 MIL-STD data bus capabilities.

b. The CATM will be deployed on both GPS equipped aircraft and non-GPS equipped aircraft.

c. The CATM will function during both GPS jamming and data link jamming conditions.

d. Target area clutter and target area context vary considerably. Requires further research.

e. Terrain, structures, target area weather, aircraft minimum flight altitudes, and day/night conditions may impact accurate flight path simulation. It may not be feasible for the CATM aircraft to simulate Unitary terminal maneuvering and dive angles.

f. All pilot displays will be identical to the displays seen in Unitary engagements.

g. The CATM may be controlled by the launch aircraft or by a controller aircraft via a data link pod.

h. Aimpoint updating is expected as the result of: 1) transfer of the aim-point from an acquisition object to the intended target, and 2) aim-point position modification to meet the necessary aim-point accuracy.

i. Target position updates for moving targets may be made

via the data link.

j. Retargeting of land and sea targets may be made via the data link.

k. Weapon launch simulation altitude may be below the target altitude.

l. CATM midcourse waypoints will be utilized to support tactics and terrain avoidance.

3. Design Considerations

a. CATM Size

The threshold maximum weapon size is XXX inches in length, XX inches in width, and XX inches in height.

b. CATM Weight

As a threshold requirement, the weight of the CATM shall not exceed 500 pounds. A maximum CATM weight of 200 is an objective.

c. Aerodynamic Design

A fatigue analysis will be necessary to insure that the structural life of the design will cover the duration of the JSOW Unitary program. Dynamic structural analysis will be performed on the CATM and aircraft airframes to determine landing loads for the envelope of worst-case landing conditions that the F/A-18 is expected to encounter.

Transonic drag will be reduced by incorporating low drag after-body configurations. The natural frequencies of the CATM structure will be determined to match the compatibility between the wing of the plane and the CATM. Adjustments should be made in the CATM structure to tailor the natural frequencies and provide a good match while satisfying other requirements.

d. Carriage Aircraft

The CATM shall have a threshold capability of carriage aboard the F/A-18C/D and the F-16C/D with an objective additional capability on the F/A-18A/B, F/A-18E/F, F-15E, F-14D, F-117, AV-8B, and the B-1B.

Flight Clearances for all Aircraft and Weapons Systems within the Navy purview (OPNAVINST 3710.7P).

NAVAIR Flight Clearance Policy (NAVAIRINST 13034.1)

Objective 1500 flight hours. Requires further research.

Objective 400 cats/traps. Requires further research.

Smart rack compatibility issues. Requires further research.

e. Aircraft Interface Definitions

To be fully capable, the CATM requires a carriage platform that is in compliance with both MIL-STD-1553B, which provides a logical interface and MIL-STD-1760 which provides an electrical interface.

(1) MIL-STD-1553. MIL-STD-1553B defines the multiplex data bus architecture that is the standard for DoD aircraft. The full implementation of this standard allows an aircraft to communicate with remote terminals, which can be in avionic subsystems, including weapons, and pass information back and forth. Most tactical aircraft are MIL-STD-1553 compliant.

(2) MIL-STD-1760. This standard defines implementation requirements for the Aircraft/Store Electrical Interconnection System (AEIS) in aircraft and stores. This interconnection provides a common interfacing capability for the operation and employment of stores on aircraft. It includes the following: the definition of the physical connector (umbilical), the electrical signal set and the logical (MIL-STD-1553) data definitions at the aircraft station interface (ASI) and at the mission store interface (MSI).

The primary interface signal sets differ for Class I, Class IA, Class II and Class IIA type interfaces. Generally speaking, however, the signal set is comprised of interfaces for high bandwidth signals, redundant multiplex

data bus signals, low bandwidth signals, fiber optic signals, a specified number of dedicated discrete signals and aircraft power. The high bandwidth interface includes the ability to transfer video, radio frequency (RF) and time synchronization signals.

The digital multiplex data interface provides redundant channels (Mux A and Mux B) for transferring digital information, store control, and store status data between aircraft and stores. The signals crossing the interface must comply with the requirements of MIL-STD-1553.

f. CATM Interface Requirements

Few aircraft types are considered completely compliant with MIL-STD-1760. This standard has been evolving since the early 1980's, hence aircraft and weapons have implemented the 'current' version of the standard at the time they were developed. This does not restrict their ability to employ the JSOW CATM, since the key ingredient for aircraft to communicate with the CATM is the implementation of MIL-STD-1553 capability at the ASI.

(1) BIT. The JSOW Unitary CATM shall have a go/no-go BIT capability, which can be initiated on and off the aircraft by both maintenance and aircrew personnel. BIT shall not exceed 5 minutes. BIT shall have a fault detection rate not less than 90%, a fault isolation rate not less than 70% to a level that supports the maintenance concept, and a false alarm rate not greater than 20%.

g. GPS Modes of Operation vs. Platform Capability

The ability of the CATM GPS to acquire and track the GPS constellation is based on the capability of the carriage platform. In cases when the CATM does not acquire GPS or loses GPS due to jamming or masking, the CATM will simulate navigation with it's own INS, using information from the aircraft navigation system obtained during the transfer

alignment or the last obtained GPS information. Some degradation of performance may result until GPS is reacquired.

The benign jamming environments are those that result in a J/S (jammer-to-signal ratio) condition at the receiver front end that is considerably less than the maximum J/S thresholds required to maintain velocity and location information. (Ref. JSOW System Specification Document, SD-901-1.) The estimated acquisition times in the benign environment include antenna performance effects. The acquisition times for the acquisition threshold J/S levels do not account for antenna performance and will be refined as that information becomes available.

The following is a description of the operational approach and capability of JSOW CATM to achieve full GPS precision navigation. The description is provided in accordance with the information available from the launch platform, from the least capable to the most capable.

(1) Non-MIL-STD-1553 Aircraft. The CATM must receive current almanac, crypto keys, SV block and AS/SA configuration, time and mission information via the CATM MIL-STD-1760 interface (umbilical connector) prior to aircraft upload. Mission information must include power-on and release time, position and velocity in accordance with the JSOW system specification. The aircraft provides GPS receiver reference oscillator heater power to the CATM while enroute to the launch point (less than 10 minutes required) via 28V DC-1.

The CATM simulates launch at the predetermined location, altitude, speed and time specified during mission planning. The aircraft must provide 115V AC power and maintain level flight and constant speed for 30 seconds prior to simulated release. Aircraft speed may be restricted from the time 115V power is applied until simulated launch to support JSOW self-leveling algorithms designed to reduce missile sensitivity to pitch and roll errors.

The CATM will not initiate GPS acquisition until after simulated release. A cold start sequence is initiated 3 seconds after simulated release when CATM attempts to acquire the first satellite (SV) C/A code and transition to the P(Y). It then proceeds sequentially to acquire C/A codes and transitions to P(Y) on the remaining visible SVs. After the four SVs considered most ideal for precision navigation are acquired and tracked, the CATM will continue to sequence a fifth receiver channel among the remaining SVs in view and include the information acquired from these for navigation.

GPS guidance capability in this mode of operation is limited to benign environments until the ephemeris data of a full set of SVs available in the target area have been acquired and P(Y) code transition for at least one SV has been achieved. Time to full GPS precision navigation solution after release is estimated to be 96 seconds.

Weapon free-flight time must be planned to provide sufficient GPS acquisition time to achieve reasonable mission effectiveness. The CATM will be limited to the preplanned route and target specified during mission planning, no self-targeting is available from this type of platform.

(2) MIL-STD-1553 Aircraft Without GPS. The aircraft provides GPS heater power during store inventory when the aircraft is powered up on the deck. The CATM will receive current GPS keys, almanac data, SV block and SA configuration, time, position, attitude and velocity data from the aircraft upon CATM power-up (115V AC), which occurs after aircraft takeoff (the power-on time may be limited to one hour prior to launch under some scenarios due to the thermal environment). An advisory will be provided to the aircrew if the thermal limits are approached.

The aircraft and the CATM will then continuously perform transfer alignment of the CATM inertial

guidance systems via messages on the MIL-STD-1553 bus. Acceptable alignment takes 30 to 180 seconds depending upon aircraft maneuvers during this period. Generally, the more the aircraft maneuvers, the better chance the CATM will have to acquire SVs. The CATM attempts GPS acquisition after GPS warmup with less than 10 minutes of heater power required during aircraft carriage. The number of SVs successfully acquired depends on the amount of the CATM antenna field of view not masked by the aircraft and the number of SVs in that field of view.

The CATM sequentially attempts to acquire the C/A code and transition to the P(Y) code on all SVs unless range uncertainty is within a given threshold (due to a high SV or a closely located second SV). There is a good probability of acquiring four SVs from under the wing on many aircraft. The pilot has the option to maneuver the aircraft to allow the CATM to acquire ephemeris data on more SVs within the hemisphere. After simulated release the CATM will sequentially reacquire (direct P(Y)) SVs that had been tracked before release and sequentially acquire direct P(Y) on SVs that ephemeris data was previously acquired. Otherwise, the CATM will sequentially attempt to acquire C/A code and transition to P(Y) for the remaining SVs within view. The vulnerability to jamming stated above applies to any post release simulation requiring C/A code acquisition prior to acquiring P(Y) code. Utilization of the fifth channel is the same for all operational modes as that described above, regardless of the carriage aircraft configuration.

Time to full GPS precision navigation solution after simulated release is estimated to be 77 seconds in a benign environment and 104 seconds in the SD-901-1 specified jamming environment (130 seconds max at 92.2% probability corresponds to the SD-901-1 requirement).

If one SV P(Y) code is acquired prior to

simulated release but a full set of ephemeris data is not, the time to full GPS precision navigation after simulated release is estimated to be 55 seconds in the SD-901-1 jamming environment. If ephemeris data is collected by the CATM prior to simulated release on four trackable SVs, the time to full GPS precision navigation is decreased by 30 seconds. In the case that four SVs are tracked during the period 60 seconds or less prior to simulated release, the reacquisition times stated for GPS aircraft with TMP (Time Mark Pulse) and RF will be achieved. If acquisition fails, initial position information and INS navigation will be utilized to determine the dispense point with possibly degraded effectiveness.

Self-targeting is possible and at short ranges is not dependant on acquiring GPS to achieve reasonable effectiveness. (3) MIL-STD-1553 Aircraft With GPS (no TMP or RF Signals to Weapon). The aircraft provides GPS heater power during store inventory when the aircraft is powered up on the deck. The CATM will receive current GPS keys, almanac, SV block and SA configuration, ephemeris, time, position, attitude and velocity data from the aircraft upon power up (115V AC) which occurs after aircraft takeoff (the power-on time may be limited to one hour prior to launch under some scenarios due to the thermal environment). An advisory will be provided to the aircrew if the thermal limits are approached.

During carriage, the CATM attempts GPS acquisition after GPS warmup (less than 10 minutes of heater power is required). The CATM attempts to acquire C/A code on the first SV in view and then transition to P(Y). It then sequentially attempts to acquire direct P(Y) code on the remaining SVs in view. After simulated launch it reacquires with direct P(Y) SVs tracked before simulated release and then continues to attempt direct P(Y) acquisition on subsequent SVs. If no SVs were acquired prior to simulated release, the

first SV C/A code will be acquired and the transition to P(Y) code will occur prior to attempting direct P(Y) on subsequent SVs.

The CATM mission effectiveness will be identical to the Unitary specifications for all ranges within the CATM simulated flight envelope. This assumes that for ranges less than that sufficient for GPS navigation, full transfer alignment stability was achieved (up to 10 minutes) prior to release. Estimated time after simulated release to full GPS navigation is 34 seconds in benign environments and 74 seconds in SD-901-1 acquisition threshold jamming environments with no SVs acquired prior to simulated release and 25 seconds when one SV P(Y) code is acquired prior to simulated release in the acquisition threshold jamming environment. In the case that four SVs are tracked during the period 60 seconds or less prior to simulated release, the reacquisition times stated for GPS aircraft with TMP and RF will be achieved.

(4) MIL-STD-1760 Aircraft with GPS and TMP Connection. The aircraft provides GPS heater power during store inventory when the aircraft is powered up on deck. The CATM will receive current GPS keys, almanac, SV block and AS/SA configuration, ephemeris, time, position, attitude and velocity data from the aircraft upon power up (115V AC), which occurs after aircraft takeoff (the power-on time may be limited to one hour prior to launch under some scenarios due to the thermal environment). An advisory will be provided to the aircrew if the thermal limits are approached.

The CATM attempts a direct P(Y) code acquisition on all SVs after GPS warmup (less than 10 minutes of heater power is required) followed by 20 time mark pulse (TMP) and time mark block (TMB) pairs (approximately 20 seconds) being sent to the CATM. The CATM must receive another 20 pairs of TMP/TMB just prior to simulated release

for optimal P(Y) code acquisition performance. After simulated release the CATM reacquires SVs tracked prior to simulated release and continues to attempt direct P(Y) acquisition on subsequent SVs. Estimated time after simulated release to GPS precision navigation is 15 seconds in a benign environment and 25 seconds in the SD-901-1 acquisition threshold jamming environment.

(5) MIL-STD-1760 Aircraft with GPS and TMP and RF Connection. The aircraft provides GPS heater power during store inventory when the aircraft is powered up on the deck. JSOW CATM will receive current GPS keys, almanac, SV block and SA configuration, ephemeris, time, position, attitude and velocity data from the aircraft upon power up (115V AC) which occurs after aircraft takeoff (the power-on time may be limited to one hour prior to launch under some scenarios due to the thermal environment). An advisory will be provided to the aircrew if the thermal limits are approached.

JSOW CATM attempts direct P(Y) GPS acquisition after GPS warmup (less than 10 minutes of heater power is required) on all SVs within the aircraft antenna field of view. After simulated launch it attempts to reacquire the SVs previously in the aircraft field of view via direct P(Y) and acquire direct P(Y) any additional SV within the CATM antenna field of view. The SV tracking priorities are reevaluated after simulated release by the CATM to optimize the navigation solution. Estimated time after simulated release to full GPS navigation solution is 8 seconds in the SD-901-1 reacquisition threshold jamming environment if full acquisition occurred prior to release.

The following figure compares data transfer bus and GPS capabilities to the carriage aircraft configuration projected IN FY00.

Table 3.1. Aircraft Model and Data Bus/GPS Comparisons

AIRCRAFT MODEL AND DATA BUS/GPS COMPARISONS					
	1553 w/o GPS	1553 w/ GPS w/oTMP, RF	1760 w/o GPS	1760 w/ GPS, TMP w/o RF	1760 w/ GPS TMP RF
F/A-18 A/B	<LOT 10				
F/A-18 C/D	<LOT 12		>LOT 12	L 12-18	?
F/A-18 E/F				X	?
F-14 D					X
F-15 E				X	
F-16 C/D				w/o TMP	
F-117				X	
AV-8 B				X	
B-1 B				X	

h. Preparation and loadout

Preparation and loadout of the CATM under extreme weather conditions is an objective.

i. Upload/Download

The maximum time for a Navy ordnance crew to load one CATM on an F/A-18 and perform post-load Built-In-Test (BIT) shall not be greater than XX (20) minutes.

j. Carriage Envelopes

The CATM shall be capable of carriage throughout the subsonic flight envelope of the above aircraft. It shall also be capable of carriage during the supersonic dash tactics of the above aircraft. The CATM carriage airspeed objective is XX

Mach/ XX Knots Calibrated Air Speed (KCAS) (whichever is less) for XX minutes. As a threshold requirement, the carriage load limit is -X.X g to + X.X g. As an objective, the carriage load limit is the same as the limits of the basic aircraft (LBA). CATM threshold and objective carriage ceilings are 40000 feet MSL and 50000 feet MSL, respectively.

k. Launch and Unitary Flight Simulation

The CATM shall be capable of effective Unitary simulation from high and low altitude with delivery tactics at various aircraft attitudes and velocities. JSOW Unitary threshold launch parameters are:

500 feet Above Ground Level (AGL) to 30000 feet MSL
Mach XX to Mach XX or XXX to XXX KCAS (whichever is less)
Off-axis launch angles of ±30 degrees from aircraft heading
Bank Delivery angles from zero to ±30 degrees
Pitch delivery angles +10 degrees to -45 degrees

Objective launch conditions are:

200 feet AGL and above
Sea level to 50000 feet MSL
Mach XX to Mach XX or XXX to XXX KCAS (whichever is less)
Bank Delivery angles from zero to ±45 degrees
Acceleration limits from +0.5 g to +5.5 g

l. Launch Range Simulation

TBD

m. CATM Data Link Selectable Power Level

TBD

n. Automatic Target Recognition

As an objective, the seeker hardware shall provide for automatic target recognition (ATR) capability. The hardware provisions should be performed to the extent that it

does not significantly impact seeker cost.

o. CATM Video Recording

TBD

p. Jettison

Jettison requirements shall be determined based upon the performance characteristics of the employing aircraft. The threshold for the jettison envelope is a safe jettison within the carriage limitations of the individual aircraft. The objective is for no jettison capabilities with the CATM weight less than 300 pounds (moment arm is insignificant).

E. MISSION DATA REQUIREMENTS

1. Mission Planning

Mission planning for use with the CATM will include all those activities performed by the mission planners to effectively utilize the Unitary weapon system against real targets in real world operational environments. Mission planning includes estimating mission effectiveness in a real world environment. Mission planning shall be performed at the O-level utilizing available mission planning capabilities. No new or unique intelligence capabilities shall be required. The mission planning times associated with the various mission scenarios shall be compatible with the high expected utilization and the number of planning assets available at the O-level.

The JSOW CATM program was initiated prior to the integration of GPS on all Navy launch platforms. As a result, the CATM does not require GPS support from the aircraft except for data originating from mission planning and transferred via a data transfer device. The CATM requires two categories of information to operate in other than a degraded mode: precise target location in the World Geodetic Survey of 1984 (WGS-84) datum and GPS data (almanac, satellite configuration and anti-spoofing status (AS/SV), time, and crypto key).

2. Target Location

Target coordinates must be defined by latitude, longitude and elevation in the WGS-84 datum. Information from other datums must first be converted to WGS-84 by the mission planning system or the aircraft. The CATM will incorporate into the target information a "terminal waypoint", as well as a terminal dive angle and altitude, which can be defined by the mission planner. These waypoint and terminal parameters will be used to set up the run-in heading and required distance to the target to optimize the data-link axis and terminal maneuver. If the planner does not specify a distance for this terminal leg, the missile will calculate a minimum distance to account for turn radius and the specified attack conditions.

a. Fixed Targets

Precise aimpoints are normally determined using imagery; therefore, the CATM requires that there be a method for translating a location on an image into precise coordinates. TAMPS, as the primary Navy mission planning system, will provide complete mission planning support, to include processing targeting quality coordinates. These coordinates may be obtained from the TAMPS internal data base, if available, or from the Digital Point Positioning Data Base (DPPDB) library, using imagery analysis equipment such as the Digital Imagery Work Station (DIWS) or other systems, which may also be queried directly without using TAMPS. The CATM will also be compatible with the AFMSS.

b. Relocatable Targets

A relocatable target is a target whose location is known, but which has the ability to move to a different fixed location after missions are planned but before the JSOW can reach the target area. (Mobile targets differ from relocatable targets in that a relocatable target is stationary during the attack). Examples of relocatable targets are surface-to-air

missile (SAM) or artillery batteries, parked LCVs, or ships at a pier. Targeting for these types of missions is similar to conventional close air support (CAS), because it requires the capability to utilize real-time intelligence. The CATM allows the aircrew to edit the target coordinates enroute to the launch point and to update target location based on the best available information from any source. (Providing the carriage aircraft is so equipped.)

Additionally, during mission planning, if a target is expected to move, or precise locating data is unavailable but expected enroute, the mission planner may allocate a radius of movement about an estimated location for the target. This will allow the planning of a weapon route and a PP-IZLAR while allowing the weapon sufficient energy to compensate for movement of the target within a specified distance. (The updated target coordinates must be entered by the pilot prior to simulated release, the CATM/weapon will not execute any search patterns.)

c. Moving Targets

JSOW Unitary has the capability to attack moving targets; however, the motion of the target increases the targeting problem for the mission planner. Since JSOW is a "bomb-on-coordinate" weapon, some provision must be made to predict the location of the target at the time the weapon will arrive at the seeker turn-on point. Possible tactics might include coordinates for tactically significant features (choke points, major road intersections, etc.) and the use of a forward air controller (FAC) or FAC-A to provide target coordinates in conjunction with a shorter launch range to keep the time-of-flight as short as tactically feasible.

Attacking moving targets at standoff ranges becomes more complex. To properly utilize the effectiveness of JSOW while launching weapons outside of point defenses, third-party targeting is enhanced by the following employment

capabilities: the ability to locate and target massed moving armies by providing multiple aimpoints along lines of communication (LOC) in WGS-84 coordinates; precise platform targeting ability at standoff ranges using WGS-84 coordinates; real-time cockpit display of tactical information, such as providing the desired time of arrival of the weapon overhead the target point, to ensure a high probability that moving targets will be under the point; location of the highest terrain between the launch point and the target area to prevent ground impact; and the ability to determine the optimum heading for impact.

While JSOW is not a CAS weapon in the traditional sense, some parallels may be drawn when attacking moving targets. Current CAS targeting methodology is cumbersome, however the information contained in the CAS brief is critical. This information must be forwarded to the attack package prior to arriving in the launch area and updated as close as possible to the launch point. A near continuous update via data-link to the launching aircraft would minimize targeting errors due to timing delays.

Any tasking requiring pilot effort on other than tactical tasks, especially in single aircrew aircraft, while in a threat envelope is detrimental to overall mission effectiveness. Therefore, the ability to pass targeting information via data-link (Multi-platform Information Distribution System (MIDS)/Improved Data Modem (IDM)/Joint Tactical Information Distribution System (JTIDS)/Surveillance and Control Data-Link (SCDL)/Tactical Digital Information Link (TADIL)/Automatic Target Handoff System (ATHS)/etc.) from a third party source to the launching aircraft is strongly desired.

For some conditions, third party or on-board targeting sensors may not be accurate enough to resolve target coordinates and, therefore, weapons must be launched at

pre-planned, GPS defined, tactically significant target points selected by the mission planners and coordinated with the launch aircraft via code words. These points would be chosen on the assumption that the locations of the moving targets are sufficiently predictable to allow a JSOW strike to be launched against the target based on predicting the target's route and speed of advance relative to the preplanned points.

d. Target Location Error (TLE)

Traditional weapons, which required a line-of-sight release, did not use absolute target location as a significant factor in weapon effectiveness. This was due to the use of relative position in weapon targeting. The weapon was released from the aircraft and traveled a predictable ballistic path to a point on the ground. It was the relative location from the launch point, not the absolute location of the desired impact point, that was critical to accuracy.

With the advent of GPS-aided weapons, absolute location has become a critical factor. A weapon, such as JSOW, which uses a GPS aided INS, will attack the point which it calculates to correspond with the target latitude, longitude and elevation in the WGS-84 coordinate system. Due to targeting and intelligence system inaccuracies, the target may be in a slightly different physical location than the coordinates marked on the targeting resource. This difference is called the target location error (TLE).

TLE is generally referred to as either horizontal (or ground plane) error or vertical error (VLE) for clarity. In general, locating data from current systems is more accurate in the horizontal plane than the vertical plane.

TLE must be combined by root-sum-square with weapon navigation error to determine the actual miss distance of the weapon. It is possible that even given a small navigation error, TLE may be large enough that the probability of hitting the target becomes very low. Some mitigation of TLE is

possible through the use of seeker-aided weapons, such as the JSOW Unitary, which allow refinement of the aimpoint in the end-game. However, even the field-of-regard of the seeker may be exceeded by the TLE at short ranges.

Because the Analytic Photogrametric Positioning System (APPS) is not capable of resolving target location with a consistent level of accuracy sufficient to be used with JSOW, the JSOW program is working with the Defense Mapping Agency (DMA) to ensure that existing systems such as the Digital Point Positioning Database (DPPDB) can supply data of sufficient accuracy to meet JSOW requirements.

F. MISSION LEVEL CONSTRAINTS

1. Return to Carrier

The CATM structure should be of a separate light weight design while retaining the Unitary avionics/electronic hardware/software functions to maximize carrier and aircraft weight, fuel, and fatigue interoperability.

2. Data Link Pod Availability

The AN/AWW-13 data link pod is an existing aircraft data link terminal that will be used to support the JSOW Unitary CATM data link function. The deployment concepts utilized to support the design of the JSOW Unitary Weapon System shall be consistent with the availability of data link pod assets. The Air Force ASQ-14 pod and the Integrated Data Link Pod (IDLP) are not compatible with JSOW.

3. Data Link Pod Reliability

The data link pod is not included as a reliability element of the weapon system; however, the data link pod and the aircraft reliability are major contributors to the successful and efficient training on the Unitary system. The employment concepts utilized to support the design of the CATM training system shall be consistent with real world reliability issues.

G. CRITICAL SYSTEM CHARACTERISTICS

1. Natural Environment

Specified in the Life Cycle Environmental Profile, SD-901-1 Appendix A.

Captive carriage vibration

Cat/Trap shock

Non-operating shock/vibration

2. Induced Environment

The induced aircraft environment is to be determined by the System Engineering Requirements Team. The induced electromagnetic environment is specified in the electromagnetic Environmental Effects Profile, SD-901 Appendix C.

H. INTEGRATED LOGISTICS SUPPORT

1. Maintenance Planning

The CATM shall be capable of being maintained using the same maintenance concept as the AGM-154 Unitary less the live ordnance and wing fold handling procedures.

2. Support Equipment

a. Container

The CATM has the objective to use an existing container.

b. Seeker Head Vacuum Restoration

TBD

3. Human Systems Integration

A principle objective of the CATM is to reduce the training burden on aircrews, ordnance and other personnel in maintaining proficiency and qualifications compared to currently employed weapons. Where applicable, the CATM shall utilize the same training capabilities as those established for JSOW.

4. Computer Resources

Tactical computer hardware developed for the CATM shall use Ada programming language in accordance with MIL-STD-1815 and be compatible with a validated Ada compiler. The CATM body shall be compatible with the selected JSOW data loader for the reloading and modification of missile embedded software, and compatible with the same data loader for the initialization and recording of BIT.

5. Other Logistics Considerations

a. *Cat/Trap Testing*

Depending on the final CATM design, Cat/Trap (C/T) testing may not be required if the C/T requirements can be satisfied by analysis. However, measurement of the environment may be important in terms of identifying seeker shock requirements. If C/T testing is determined to be required, the following issues need to be addressed:

Trap/Cat testing requirements as required.

MDA would have to instrument the aircraft rack.

Accelerometer and strain gage data would need to be either TM down to the ground (i.e., T-pad), or recorded internally in the CATM.

It is possible that only Trap data would be required.

b. *Special Instrumentation Pod (SIP)*

If required, the following may have to be investigated:

Pod documentation.

Air loads.

Design data package.

Physical characteristics.

Operational Characteristics.

Pod availability.

I. INFRASTRUCTURE SUPPORT AND INTEROPERABILITY

1. Command, Control, Communications and Intelligence

TBD

2. Transportation and Basing

TBD

3. Standardization, Interoperability, and Commonality

The JSOW CATM shall be compatible with MIL-A-8591 stores interface requirements and MIL-STD-1760, Class II, aircraft/store electrical interconnection requirements.

4. Mapping, Charting, and Geodesy Support

TBD

5. Environmental Support

TBD

J. FORCE STRUCTURE

AWW-13- currently about 150 data link pods in the fleet.

K. SCHEDULE CONSIDERATIONS

1. IOC

Development plan/schedule...1999 to 2001. Target date for implementation into the fleet is 2003.

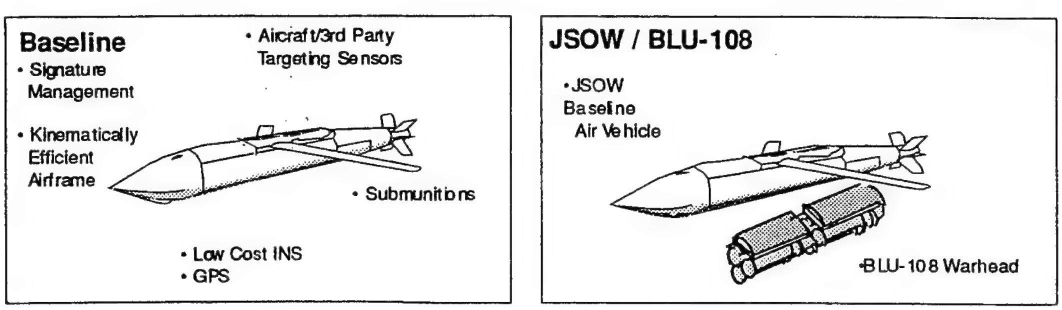
IV. A "QUICK LOOK" AT THE COMMONALITY OF WEAPON COMPONENTS AND FUNCTIONALITY FOR THE DESIGN OF A MULTI-WEAPON CAPTIVE AIR TRAINING MISSILE

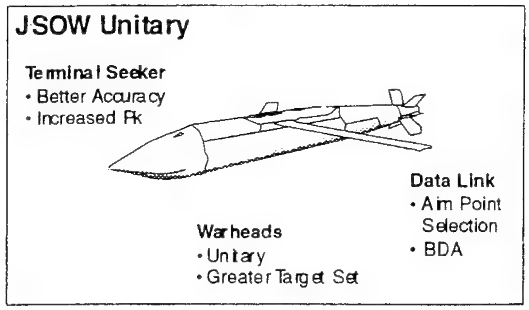
Consider this: A pilot of one of the most technologically advanced Strike aircraft in the world is flying a training mission with a single, light weight, multi-weapon CATM onboard. He selects 'CATM' on the multipurpose display and is presented with a selection of all the variants of JSOW, JDAM, SLAM, IR MAVERICK, and TSSAM. He boxes 'UNITARY', the aircraft's Stores Management System relays the command to the CATMs Guidance Electronics Unit that then activates the partitioned UNITARY processor. The UNITARY processor in turn commands all the CATM functions and aircraft interfaces necessary for 100% JSOW UNITARY weapon prelaunch and postlaunch simulation. After target flyover, the pilot wishes to train on an unsuspecting ship in the harbor. He deselects 'UNITARY', and boxes 'IMAV', the SMS relays... Multiple weapon training on every flight.

This chapter introduces the commonalities of JSOW, SLAM, and the IR MAVERICK. JSSAM is a powered variant of JSOW and is in effect included under the JSOW discussions. TSSAM specifics are not available.

JSOW VARIANTS

Figure 4.1. JSOW Variants

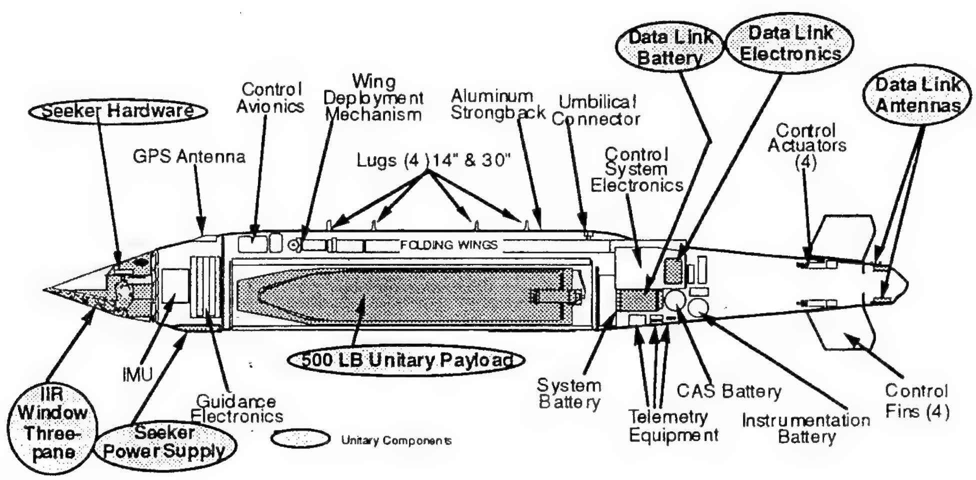




The design and procurement strategy of the JSOW system established an initial baseline INS/GPS weapon from which low risk, evolutionary upgraded components could increase accuracy, enhance kill capability and include more targets. Currently, there are three configurations, or variants, of the JSOW vehicle: JSOW Baseline, JSOW BLU-108, and JSOW Unitary. Unitary is different from the Baseline and BLU-108 variants in that the Unitary utilizes an IR terminal seeker and data link with Man-in-the-Loop (MITL) capabilities.

JSOW UNITARY (AGM-154C)

Figure 4.2. JSOW Unitary



Aircraft Interfaces:

Unitary performance and tactical flexibility depend on the capability of the specific launch platform to provide an electro-mechanical interface in accordance with MIL-STD-1760A, Class 2 requirements and MIL-STD-8591A. When integrated with aircraft incorporating nonstandard electrical interfaces, the JSOW Unitary will use existing signals with expected reductions in mission capabilities and tactics.

Seeker:

The Unitary seeker subassembly is unique to JSOW Unitary and provides a re-imaging imager with a focal plane array detector. More specifically, it is a scanning, long-wave imaging infrared (LWIR) seeker operating in the 8-10 micron bandwidth and is made up of two major subsystems, the sensor assembly (imager optics, a scanner, focus/athermalization cell, the dewar/detector, closed cycle cooler, and imager housing) and the Terminal Guidance Electronics (TGE).

The sensor optics consist of three Germanium (Ge) flat plate lenses and three flat reflective mirrors, which are uncommon in other tactical missiles; however, segmented windows have been used in low signature missiles such as TSSAM. The seeker gimbal rate sensor is a solid state gyro manufactured by Systron Donner or Condor Pacific and is also being incorporated into the Maverick missile. The maximum diameter of the seeker portion is estimated to be 7.5 inches.

The TGE consists of three circuit card assemblies (CCAs) located in the GEU chassis.

Guidance Electronics Unit (GEU):

Quad C40 Processor CCA- The computer sensor control interface (CSCI) is the software that implements the terminal tracking functions, sensor hardware control, and computer

interfaces. Total processing capacity is 182 million instructions per second developed in Ada.

Normalization/reformatter CCA- Mainly digital processing board with some analog functions implements normalization of the imagery and reformats the video for display on the aircraft and drives the data link.

Sensor Control CCA- Combination analog and digital circuit card to control the sensor analog functions. It commands the sensor operation including digital stabilization, video normalizing, gimbal pointing and built-in-test.

Mission Computer Interface. This function maintains communication with the Mission Computer. It accepts navigation data and mission parameters and outputs aimpoint information and status data.

INS/GPS:

INS specifics are not available. One GPS antenna is located on the top of the guidance section, just aft of the seeker head.

Weapon Data Link:

The weapon data link includes the weapon data link terminal (WDT) and the data link antenna. Both the narrow band command receiver and the video bandwidth transmitter operate in the L-band frequency spectrum. The video phase modulation transmitter has both a low RF power output, 1 to 2 watts, and a high RF power output, 45 watts. RF devices to be used are common to most weapon data link terminals, including SLAM, SLAM-ER and TBIP.

Power Requirements:

The Power Subsystem consists of all components needed to

supply regulated 28 V DC power to the electrical and electronic components of the AUR and is identical to Baseline with minor differences. The Power Converter is also identical to the Baseline and supplies 11 to 13.4 A of 28 V DC power for all captive flight regimes following initialization.

The Torque Drive CCA includes on-board regulation for the raw 28V power it receives from the Unitary power converter and battery.

The weapon data link requires less than or equal to 400 watts of electrical power. An upgraded (or additional) power converter will be necessary to support the power requirements of the seeker and data link.

JSOW BASELINE (AGM-154A) and BLU-108 (AGM-154B)

Seeker: None.

Guidance Electronics Unit (GEU):

Processors- The mission computer hardware in the Baseline and the Unitary are identical with minor software changes in terminal guidance and control.

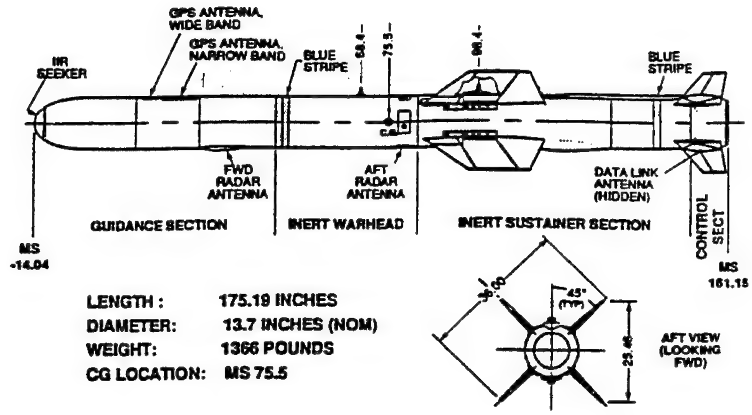
INS/GPS: Same as Unitary

Power Requirements:

The Power Subsystem consists of all components needed to supply regulated 28 V DC power to the electrical and electronic components of the Baseline and BLU-108 are identical to Unitary with minor differences. The Power Converter is also identical and supplies 11-13.4 A of 28 V DC power for all captive flight regimes following initialization.

STANDOFF LAND ATTACK MISSILE (SLAM) (AGM-84E)

Figure 4.3. SLAM

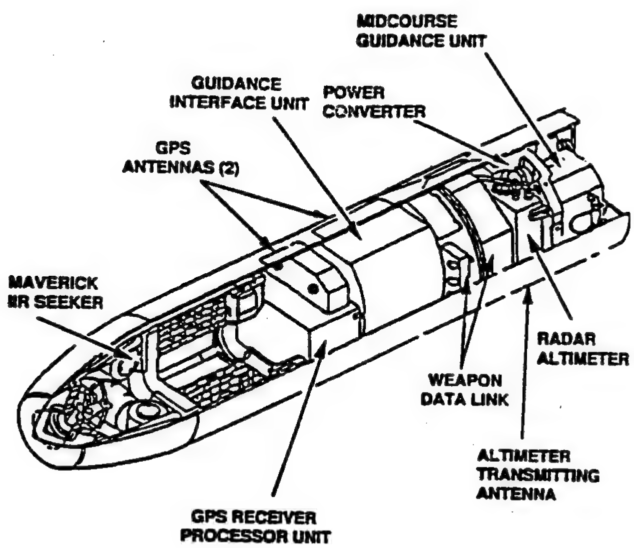


SLAM evolved as a near term solution to critical deficiencies in 1980's TV and IR guided weapons and to satisfy intermediate tactical needs between long range cruise missiles and short range free-fall munitions in the land attack scenario. Though primarily a land strike weapon, SLAM also has a supplemental capability as an anti-ship weapon against medium and large ship targets in port. The integration of GPS accuracy and Man-in-the-Loop (MITL) control provides precise real-time targeting capability and aimpoint control. The guiding principle in the SLAM design combined the technology of Harpoon, Maverick, and Walleye missile components to produce a near term, intermediate range strike weapon system.

The SLAM CATM is a derivative of the baseline SLAM airlaunch configuration, which uses production SLAM hardware and software. The SLAM CATM and tactical SLAM missile are completely identical with regard to guidance system equipment and software, aircraft physical interface, external aerodynamic configuration, and mass properties. The key

physical difference between the SLAM CATM and other CATMs is the amount of ballast (unwanted weight) present in the CATM. An inert warhead section is used in place of the active warhead section, the missile battery and all pyrotechnic initiator devices are inert, and ethylene glycol is substituted for the JP-10 fuel. Extra weight and larger shapes for the CATMs translate to less mission fuel and more flight restrictions.

Figure 4.4. Forward SLAM Body



Seeker:

The Maverick IIR seeker is used in the SLAM as the terminal guidance sensor. The seeker provides day and night capability in good to marginal weather conditions. It consists of a dual field-of-view infra-red imager, mounted in a two-axis gimbal, capable of developing a video presentation of the target acquisition, lock-on, and tracking.

Guidance Interface Unit (GIU):

The GIU interfaces the various avionics systems in the guidance section by providing signal buffering and logic operations.

Midcourse Guidance Unit (MGU)- Consists of a Digital Computer/Power Supply (DC/PS) and an Attitude Reference Assembly (ARA). The DC/PS is a general purpose digital computer and power supply and performs the flight control computations. The power supply conditions and converts missile avionics power for use by the computer and ARA. The ARA is a three-axis strap down sensor, consisting of accelerations and rate sensing gyros. The AA provides inertial measurements for use by the navigator and autopilot.

INS/GPS:

The NAVSTAR GPS Receiver Processor Unit (RPU) consists of a single-channel sequential GPS satellite receiver, receiver processor (RP), and navigation processor (NP). The RP and NP develop range measurements from the GPS satellite system, and accept inertial measurements from the Midcourse Guidance Unit. These data are used to determine the location, velocity, and attitude of the SLAM. Two GPS antennas (wide and narrow beam) are located on the top of the guidance section.

Weapon Data Link:

The Weapon Data Link (WDL) consists of a data link command receiver and a video transmitter thereby providing two-way radio frequency communication between the SLAM CATM and the control aircraft. The WDL provides the means to perform SLAM post launch control after the missile and aircraft have separated. The WDL may also be used to perform

SLAM prelaunch operations if CLS commands (via the umbilical) are not available or not desired.

Radar Altimeter:

The Radar Altimeter uses two antennas (one transmit and one receive) to measure altitude and altitude rate. This data is used by the flight control program to maintain programmed terrain clearances.

Video Tape Recorder: None

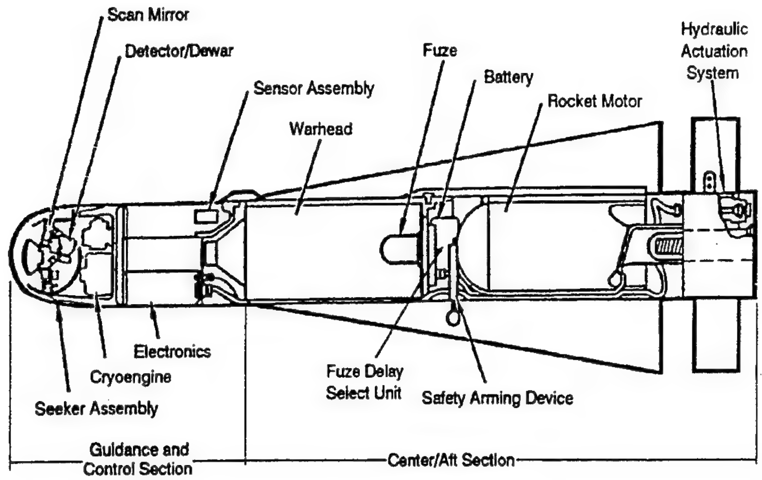
Power Converter:

The Power Converter converts aircraft 115 VAC power into 28 VDC CATM avionics system power. Since the CATM internal battery is inert, the power converter is the sole source of CATM 28 VDC avionics power in both the prelaunch and the SIMFLIGHT captive carry operating modes.

IR MAVERICK (AGM-65F)

The IR Maverick is a rocket propelled missile that requires seeker head lock-on prior to launch and is not controlled post launch. It operates during daylight, darkness, in some degraded weather conditions and is primarily for use against targets requiring instantaneous or delayed blast fuzing, such as concrete fortifications, earth covered bunkers, large structures, and ships. The warhead is also effective against armored vehicles, radar vans, boats, and small buildings. The system is designed to enable multiple launches per pass in a target-rich environment with rapid target acquisition features.

Figure 4.5. IR MAVERICK



Seeker:

The IR optical path of the system is through a series of lenses, mirrors, and a detector array, and it operates in the 8-11.5 micron region.

The seeker gyro is a free gyro in two axes and is encased in a zinc sulfide dome window. The physical limits of the gyro gimbals are left and right 42 degrees, 30 degrees up, and 54 degrees down. Software stops the seeker 2 degrees short of these limits to prevent possible seeker head damage upon contact with the gimbal stops. Electrical power application to spin up the seeker gyro begins with weapon selection and the specification allows a maximum of three minutes for the seeker gyro to reach operating speed.

A dual field-of-view capability has been incorporated to provide two selectable scene magnifications. Wide field-of-view (WFOV) provides increased target area orientation, while narrow field-of-view (NFOV) provides maximum launch ranges and improved target identification.

The missile video, as presented to the cockpit display, is overlaid with display symbology. When the contrast switch is set to Hot-on-Cold, the seeker will lock-on to a white target with white symbology, and when set to Cold-on-Hot, the seeker will lock-on to a black target with black symbology: The tracking gate is adaptive in size and will expand in each axis independently to adapt to target size and shape.

Guidance Control System (GCS):

The GCS contains 13 electronic circuit cards connected to a common mother board. They control aircraft power conversions, seeker gyro rotation speed, missile controls and logic. The digital computer allows the missile to make logical decisions prior to, during, and after launch.

INS/GPS: None.

Data Link: None.

Video Tape Recorder:

The video tape recorder assembly is easily accessible through the tail of the CATM. The recorder will run and expend tape any time video is present on the cockpit display and stops recording when the missile station is deselected. Maximum recording time is 2 hours.

Power Requirements:

The thermal battery provides 30 V power for 105 seconds during flight.

COMMONALITY

The CATM must perform all functions necessary to provide the aircrew with a realistic training scenario for all cockpit displays, INS/GPS navigation, data link functions, seeker head functions, and Man-in-the-Loop operability.

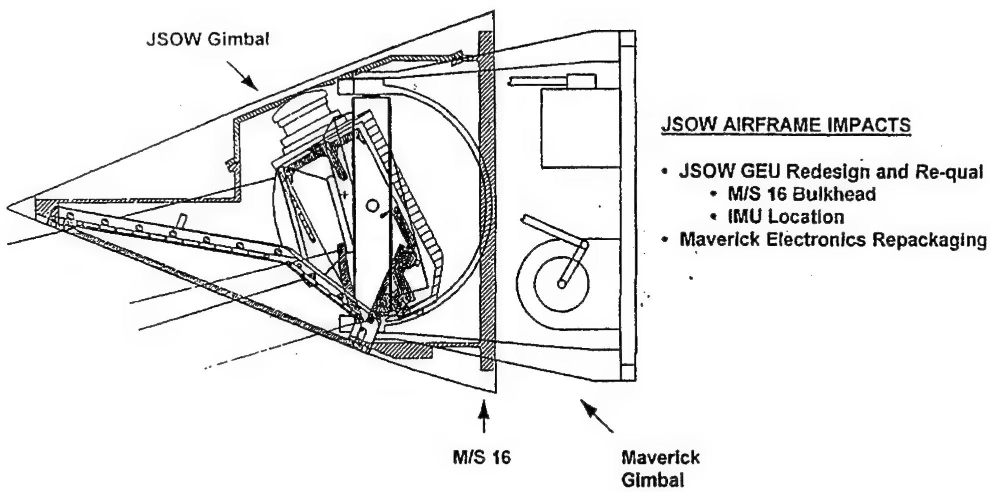
Table 4.1. Weapon Component Commonality

WEAPON COMPONENT COMMONALITY							
	UNTARY	BASELI	BLU108	JDAM	SLAM	IR MAV	TSSAM
MILSTD-1760	X	X	X	X	X		X
FOCAL PLANE ARRAY	X			X			X
IR MAV SEEKER					X	X	
MULTI FCN PROCESSORS	X	X	X	X	X	X	X
INS/GPS	X	X	X	X	X		X
DATA LINK	X			X	X		?
RDR ALTIMETER					X		
IDEO RCDR						X	
POWER-OTHER THAN 28 VDC	X			X	X		X

A major point of discussion is the difference between the newer focal planer array seeker and the older Maverick seeker. If the resolution and performance differences are a factor, then a single CATM body could be designed to accommodate each seeker head and associated software. If a weapon is ever

upgraded to the planar array seeker, then it would involve only a software change in an existing CATM. The figure below compares the physical sizes of the two seeker heads.

Figure 4.6. JSOW and IR MAVERICK Seeker Head Size Comparison



The concept of centralizing CATM development and designing a light weight, multi-weapon CATM is thought to be an attainable reality with significant training contributions for USN, USMC, and USAF pilots in vital mission areas with increased savings in maintenance man hours, lower fuel consumption, and less government and industry overheads. Factors critical to obtaining those objectives are the software/hardware integration issues involved in operating with different combinations of software, seeker head, data link, and INS/GPS functions.

V. INS/GPS SYSTEM PRELIMINARY DESIGN

A. INTRODUCTION

This chapter discusses a design of a completely integrated INS/GPS navigation/control system. The system was designed using a verication model with known stability derivatives and performance criteria. This ensured proper system performance prior to the insertion of JSOW parameters and JSOW simulation that will be conducted by CDR(S) Wagner during the two quarters following this thesis.

The design verification aircraft was the Cessna Citation II, aircraft D in Roskom. The trim and aircraft parameters were:

Vt0=677 feet per second
h0=40000 feet
alpha0=2.7 degrees
beta0=0 radians
S=230 square feet
b=34 feet
cbar=7 feet
rho=0.00058 slugs per cubic foot
CTx1=0.335 non dimensional
weight=13000 pounds
g=32.174 feet per second squared

A synopsis of the development of the equations of motion, sensor models with Kalman filter and controller is presented, a linear solution was developed and checked, followed by implementation on the nonlinear system. Plots of positon, velocity and acceleration errors are also presented to verify that the system performed satisfactorily in the presence of sensor noise and biases.

B. EQUATIONS OF MOTION

1. Overview

Three different coordinate systems were used in the development of the Equations of Motion (EOM); tangent plane, body fixed, and wind coordinate systems. The tangent plane coordinate system {u} is a local-level, inertial system, which is fixed at one point on the earth. The two horizontal axes are always normal to the local gravity vector so that the plane formed by these two axes is tangent to the earth. The vertical axis is therefore normal to the horizontal plane. The body-fixed coordinate system {b} uses the aircraft's center of gravity as its origin and is defined using the right hand rule. The wind coordinate system {w} has its x axis aligned with the relative wind.

For the EOM, we defined twelve states and four control inputs to solve for use in our simulation. These are listed in Table 5.1.

Table 5.1 Summary of States and Control Inputs

States		
u	${}^{B}u_{BO}$	x-component in {b} of linear velocity
v		y-component in {b} of linear velocity
w		z-component in {b} of linear velocity
p	${}^{B}w_{B}$	roll rate in {b}
q		pitch rate in {b}
r		yaw rate in {b}
Φ	Λ	roll angle
θ		y-axis pitch
Ψ		z-axis yaw

x	${}^{U}P_{BO}$	x-position of aircraft c.g. in {u}
y		y-position of aircraft c.g. in {u}
z		z-position of aircraft c.g. in {u}
Control Inputs		
da	u	incremental aileron deflection
de		incremental elevator deflection
dr		incremental rudder deflection
dt		incremental thrust

2. Equations of Motion

The first part of the design project was to develop a model for the aircraft equations of motion (EOM). The derivation of the EOM for an aircraft with six degrees of freedom consisted of two parts. The first determined the EOM for any given rigid body in space and was dependent only on the linear and angular momentum of the body. The second calculated the aerodynamic, gravitational, and thrust forces acting on a particular aircraft, which were generally described by the aircraft's stability and control derivatives.

Calculation of the linear equations of motion started with Newton's law, F=ma. Applying rotations between body and tangent plane coordinate systems yielded equation 5.1.

$$ {}^{B}F = m(d/dt({}^{B}u_{BO}) + {}^{B}w_{B} \times {}^{B}u_{BO}) \tag{5.1} $$

The equations for angular accelerations were derived for the aircraft c.g. by applying the Coriolis theorem to Euler's law, $d/dt({}^{B}A) = {}^{B}N$, which states that the rate of change of angular momentum (A) is equal to the applied torque (N).

Substituting ${}^{B}I\,{}^{B}w_B$ for ${}^{B}N$, where ${}^{B}I$ is the aircraft inertia tensor, and performing the math yielded equation 5.2.

$$ {}^{B}N = {}^{B}I\ d/dt({}^{B}w_B) + {}^{B}w_B x({}^{B}I\ {}^{B}w_B) \tag{5.2}$$

Solving equations 5.1 and 5.2 for the time derivative terms gave equation 5.3.

$$ \frac{d}{dt}\begin{bmatrix} {}^{B}u_{BO} \\ {}^{B}w_B \end{bmatrix} = \begin{bmatrix} -{}^{B}w_B \times {}^{B}v_{BO} + \frac{{}^{B}F}{m} \\ -{}^{B}I^{-1}({}^{B}w_B \times {}^{B}I\,{}^{B}w_B) + {}^{B}I^{-1\,B}N \end{bmatrix} \tag{5.3}$$

The next step was to solve for the external forces ${}^{B}F$ and moments ${}^{B}N$ that act on a particular aircraft, which are due to aerodynamic, gravitational and thrust effects. The aerodynamic forces and moments were determined by using a first-order Taylor series expansion around a nominal trim point. These equations incorporated stability and control derivatives as well as control inputs. Gravitational forces acting on the aircraft resolved in {b} were calculated by pre-multiplying the gravitational forces in {u} by the appropriate rotation matrix. Moments due to gravity acting on the body were zero since the aircraft c.g. was chosen as the origin for {b}. Forces due to thrust were calculated by multiplying the nominal thrust by a control term, which was equal to 1 for the cruise setting chosen. Moments due to thrust were calculated by multiplying nominal thrust by the engine moment.

Equations were also needed to solve for the final six states. These equations required the first six states in order to be solved. The equations were

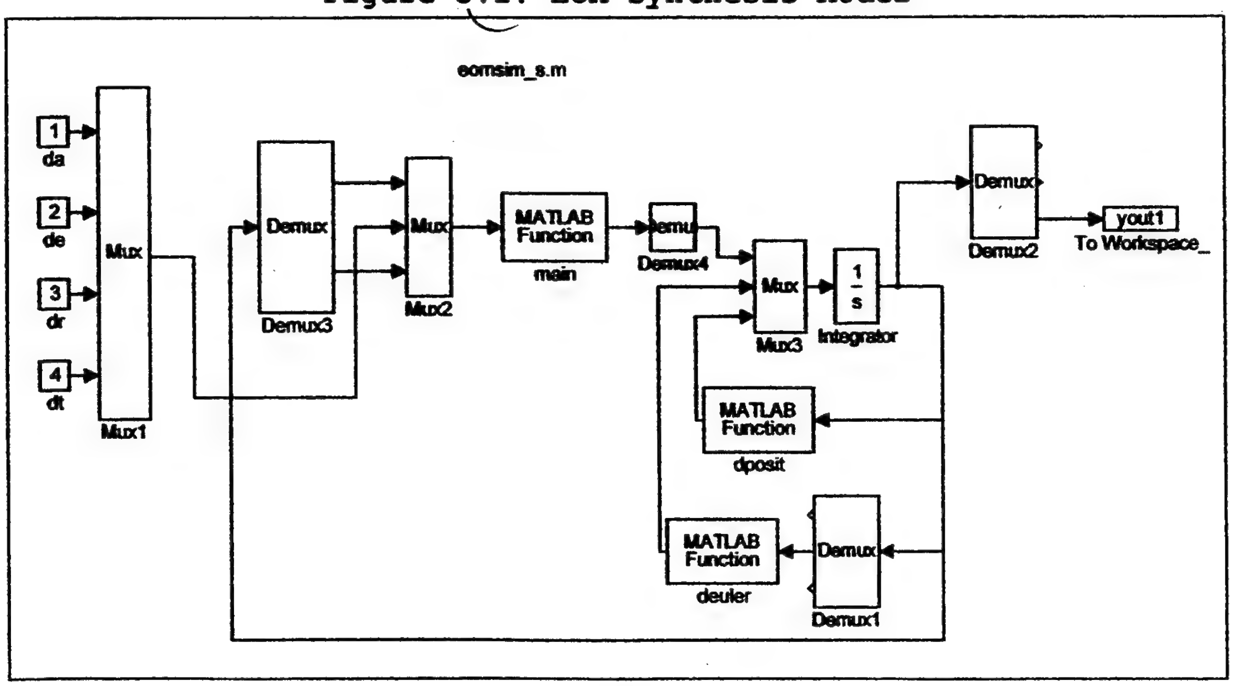
$$ {}^{u}\dot{P}_{BO} = {}^{u}_{B}R\,({}^{B}u_{BO}) \tag{5.4}$$

$$\dot{\Lambda} = Q(\Lambda)\,{}^{B}w_{B} \tag{5.5}$$

where $Q(\Lambda)$ is a rotation matrix from {b} to {u} using euler angles. Also, $\theta=\alpha+\gamma$, where α is angle of attack, and γ is flight path angle equal to zero for straight and level cruise.

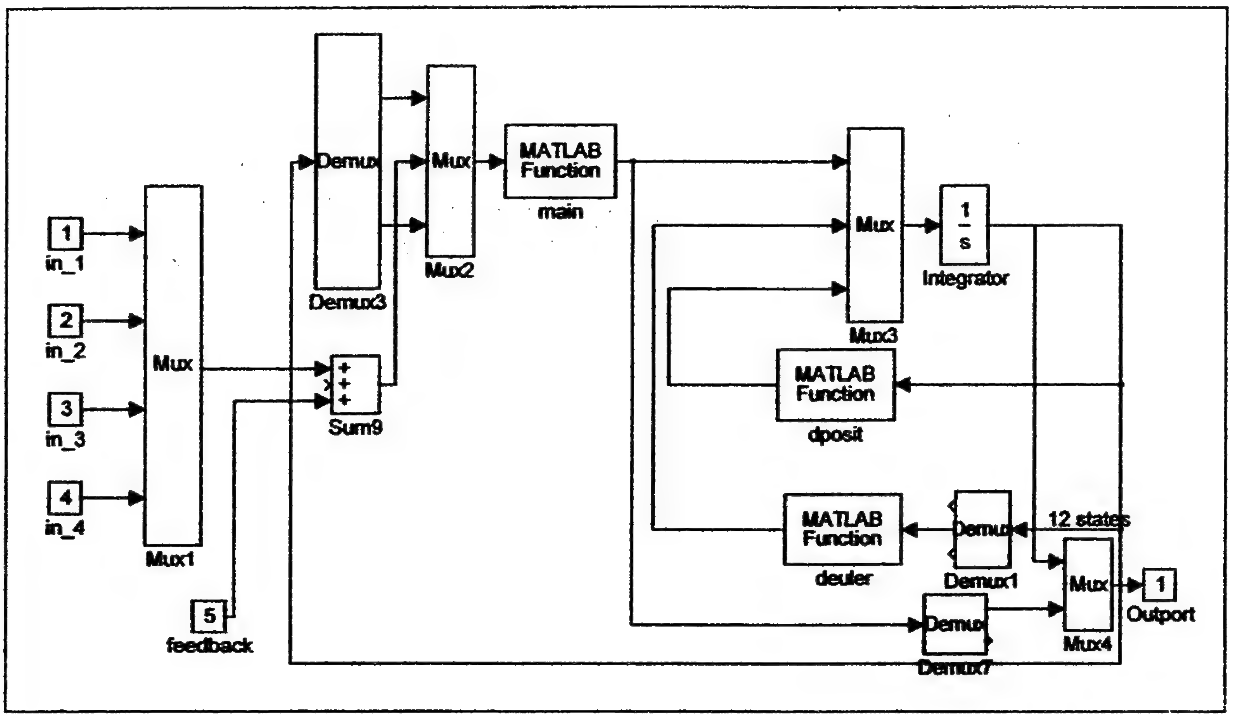
Once the EOM were derived, the next step was to write MATLAB code for the equations and to develop a SIMULINK model. Function *main.m* calculated the linear and angular accelerations for the model, and function *deuler.m* calculated $d/dt(\Lambda)$. Throughout the project we were able to troubleshoot *main.m* by inserting the initial guess values and checking that the output accelerations were indeed near zero for our straight and level cruise flight condition. Two diagrams were used to simulate EOM. Figure 5.1 depicts *eomtrim_s* the first of the two diagrams used, which determined trim values for the states and control inputs for our given flight condition. Only the first nine states were used in this part since finding a trim value for position does not make sense.

Figure 5.1. EOM Synthesis Model



The second diagram, depicted in Figure 5.2, included position and was our complete EOM model. Function *dposit.m* calculated d/dt($^{U}P_{BO}$). The trim values calculated in the preceding step were used to initialize the integrator and provide control input values. Once the diagram was complete, the *linmod* command was used to linearize the model about our trim point. This provided a state space representation of our linearized model, which allowed the calculation of the aircraft eigenvalues.

Figure 5.2. Complete EOM Model



In order to verify our EOM model, we needed to use data for an aircraft whose characteristics were well known and previously calculated using an independent source. Roskom was used as this source. The aircraft used was representative of a medium sized, high performance, business jet found in Roskom at a maximum weight cruise condition at 40,000 feet and 0.7

Mach. The steps outlined above were performed and the calculated eigenvalues compared with those given in Roskom. Table 5.2 summarizes the results.

Table 5.2 Eigenvalue Comparison

Mode	Roskom	Model
Short Period	-0.994 ± 2.64i	-0.995 ± 2.627i
Phugoid	-0.00529 ± 0.0904i	-0.0064 ± 0.0915i
Dutch Roll	-0.0585 ± 1.684i	-0.072 ± 1.673i
Spiral Mode	0	0
Roll Mode	-0.5	-0.49

The eigenvalues calculated by our model were within the 5 to 10% of eigenvalues in Roskom.

C. NAVIGATION SYSTEM

1. Sensor Modeling

The linear and rotational acceleration, velocity and position outputs of the EOM model, satellite positions, and filtered noises were used to calculate satellite pseudoranges and noisy linear and noisy rotational accelerations and velocities.

a. Accelerometers

The accelerometers were modeled as first order low pass filters excited by white Gaussian noise, with a cutoff frequency of 2 rad/sec. Additionally, a bias of 0.1 percent was added to the accelerometer model to simulate axis mis-alignment errors.

b. Rate Gyros

The rate gyros were modeled like the accelerometers above.

c. Inclinometers

The pitch and roll inclinometers, and magnetometer were modeled as first order high-pass filters excited by white Gaussian noise with a cutoff frequency of 2.5 rad/sec.

d. Linear Velocities

The linear velocities, pitot tube, were modeled like the inclinometers above.

e. Pseudoranges

The aircraft position ${}^{u}P_{bo}$ derived from the EOM was multiplexed with all satellite positions to create a single column vector. This vector was used by the MATLAB function *exact.m* to calculate geometric ranges from the aircraft to the four highest satellites. The program defined the Earth's semi-minor and semi-major ellipsoid axis, flattening and eccentricity factors, and converted the tangent plane position to geodetic latitude, longitude and height. The tangent plane rotation matrix ${}_{e}^{u}R$ converted from {e} to {u} and the rotation matrix ${}_{UEN}^{NED}R$ rotated from {UEN} to {NED}. Satellite ranges and elevation angles were defined in the tangent {u}, body {b}, and ECEF {e} planes and were solved by vector addition. The body (aircraft) vector was redefined in {e} by equation 5.6,

$$ {}^{e}P_{bo} = {}_{u}^{e}T \; {}_{UEN}^{NED}R^{-1} \; {}^{u}P_{bo} + {}^{e}P_{ou} \tag{5.6} $$

and the position of the tangent plane {u} was defined in {e}, shown in equation 5.7.

$$ {}^{e}P_{ou} = \begin{bmatrix} (N+h)\cos(lat)\cos(long) \\ (N+h)\cos(lat)\sin(long) \\ N\sin(lat) \end{bmatrix} \tag{5.7} $$

where N was the radius of the Earth at the lat/long of the center of the tangent plane, and h was its height. The satellite ranges (ρ) from the body are defined in equation 5.8.

$$\rho_b = \| {}^eP_{sat} - {}^eP_{ou} - {}^eP_{bo} \| \tag{5.8}$$

and the satellite positions defined in {u} are

$${}^u\rho_{sat\,u} = {}^u_eT({}^eP_{sat} - {}^eP_{ou}) \tag{5.9}$$

and as defined in {b} are

$${}^uP_{sat\,b} = {}^uP_{sat\,u} - {}^uP_{bo}. \tag{5.10}$$

These calculations were verified by $\rho_b = \| {}^uP_{sat\,b} \|$. To determine the order of the satellites by highest to lowest elevation, a normalized altitude difference vector was created by

$$altnorm = \frac{{}^uP_{sat\,b(z)}}{\| {}^uP_{sat\,b} \|} \tag{5.11}$$

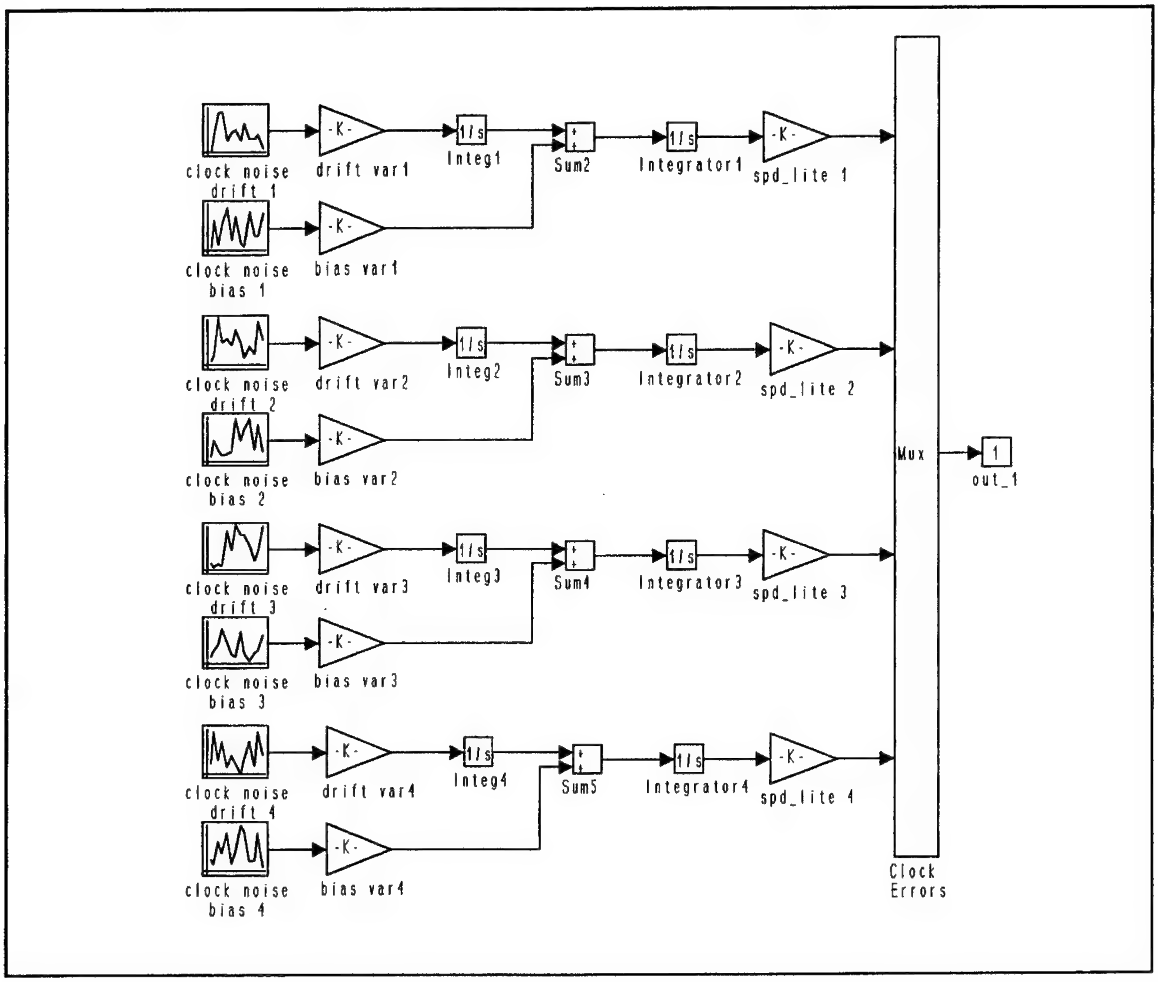
The vectors were sorted from largest positive (above the body plane) to largest negative (below the body plane) and the corresponding pseudoranges of the four highest satellites were used in the remainder of the system. These ranges were exact and to simulate realistic errors, we added white noise to represent inaccuracies in course acquisition (C/A) and in receiver and satellite clocks. Ephemeris error, receiver noise, tropospheric delay, and dilution of precision were not modeled.

f. Clock Model

The clocks were expected to have both a bias and a drift that degraded their accuracy with time. This was modeled, as shown in Figure 5.3, where a zero mean white Gaussian noise (drift) was integrated, a bias was added, then integrated again to obtain time inaccuracies. These times were

multiplied by the speed of light to convert to range errors, then were added to the pseudoranges.

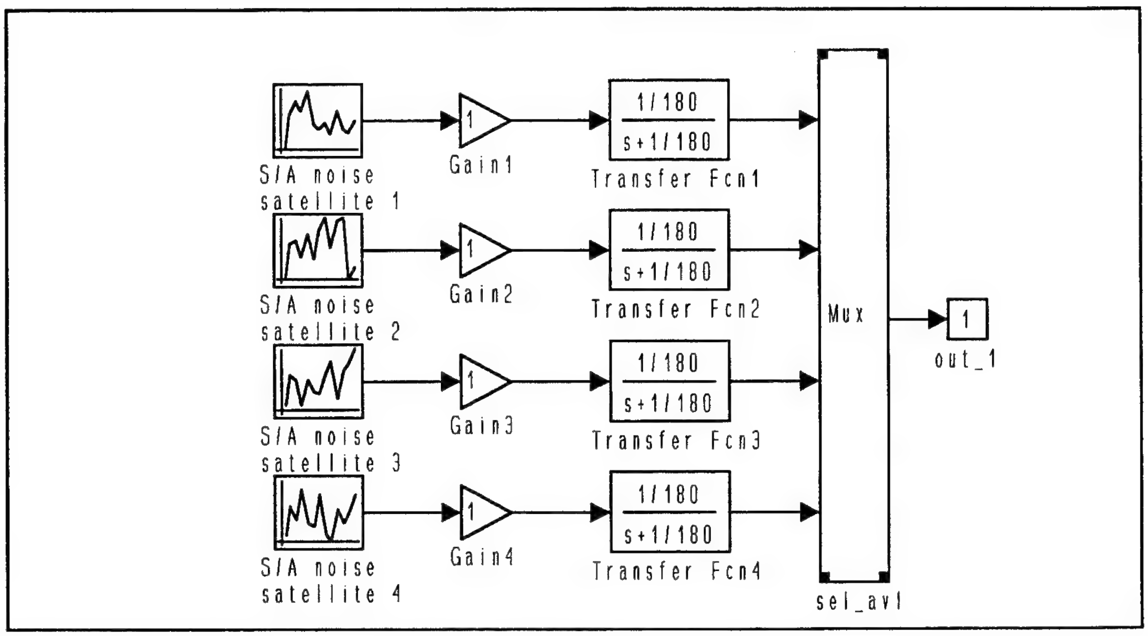
Figure 5.3 Clock Model



g. Selective Availability (S/A) Model

When the receiver first acquired a GPS satellite, it operated in the C/A mode until crypto sequencing allowed it to enter the S/A mode. The greater navigational errors in the C/A than in the S/A modes were simulated by noise added to the pseudoranges through a low pass filter with a time constant of 180 seconds (or at a cutoff frequency of 1/180 Hz). Our model is shown in Figure 5.4.

Figure 5.4 Selective Availability Model



2. Position Kalman Filter

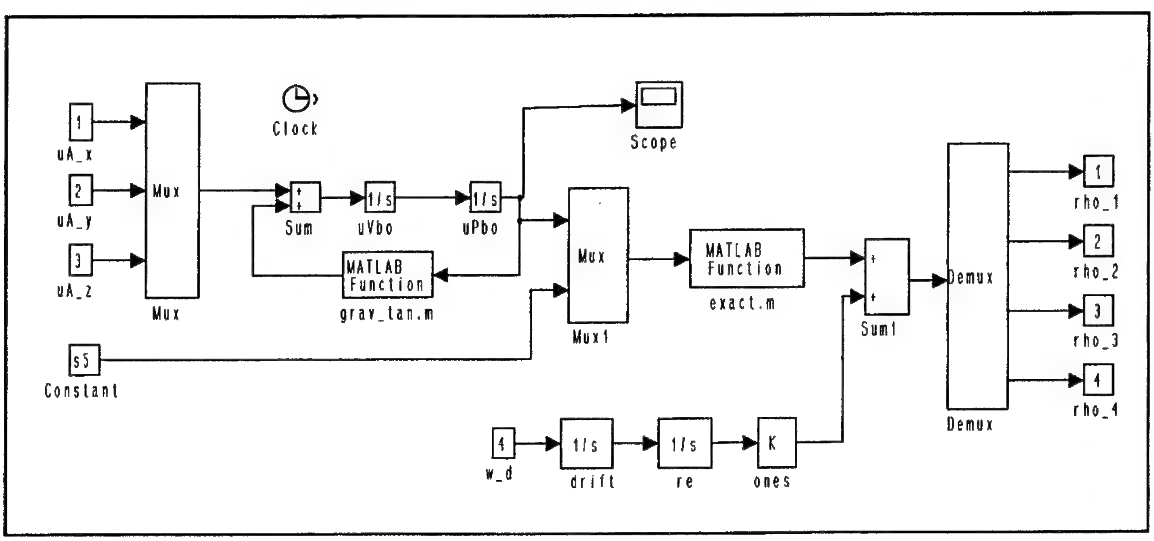
a. *Navigation Model*

Navmodel, shown in Figure 5.5, was used to develop the open-loop A,B,C, and D matrices contained in the equations:

$$\dot{x}=Ax+B_1w+B_2u$$
$$y=Cx+Du+v \qquad (5.12,\ 5.13)$$

The model had three inputs for the linear body accelerations and integrator initial conditions of zero. The function *grav_tan.m* computed the gravity vector in the tangent plane as a function of the body's position obtained from the second integration of the accelerations in that plane. The gravity term was added to the linear accelerations. The function *exact.m* used this integrated position and the satellite positions to calculate the pseudoranges to the four highest satellites. The noise model was simply a single, no value input integrated twice and added to the ranges. The open-loop matrices were obtained by linearizing the navmodel with the MATLAB command *[a,b,c,d]=linmod('navmodel')*.

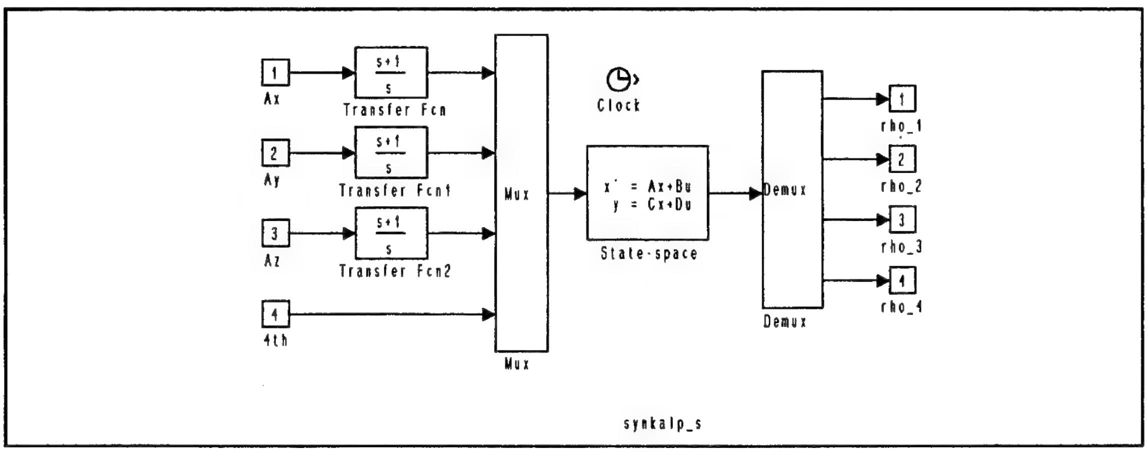
Figure 5.5 Navigation Model



b. *Synthesis Model*

The synthesis model introduced three zeros at s = -1 (one for each acceleration axis) as shown in Figure 5.6. The open-loop synthesis matrices were obtained by linearizing the synthesis model with the command *[as,bs,cs,ds]= linmod('synthesis')*. The addition of three integrators by placing three zeros at s = -1 resulted in the number of states increasing from five to eight and transmission zeros of -1,-1,-1. The synthesis matrices were examined to determine the order in which MATLAB placed the states during its calculations.

Figure 5.6 Synthesis Model



The Kalman gains (*l*) were calculated using the MATLAB command *LQE,* where the process noise W and the sensor noise V were identity. L was the gain matrix in the Kalman filter defined by $\dot{x}=Ax+Bu+L(z-Cx-Du)$ and produced an optimal estimate of x. Using the command;

l=lqe(as,bs,cs,eye(4),eye(4)),

gave l =

-0.1451	2.7513	-4.5695	-0.5344
0.5604	-2.1142	0.9664	1.4985
3.0316	-2.1917	1.6290	-0.0600
-0.6572	1.9412	-1.1070	0.6434
-0.0839	0.8427	-0.1734	0.5027
0.3480	0.6458	-2.9503	-0.6520
0.1567	-1.4111	0.0338	1.8284
2.5289	-0.4805	0.7063	0.2154
0.1983	-0.0404	-0.9524	-0.2278
-0.0203	-0.5323	-0.1795	0.8271
0.9763	0.0696	0.1748	0.1067

The eigenvalues of the Kalman filter were:

-1.0516 + 1.1331i
-1.0516 - 1.1331i
-0.7924 + 0.9659i
-0.7924 - 0.9659i
-0.5379 + 0.7457i
-0.5379 - 0.7457i
-0.2806 + 0.3810i
-0.2806 - 0.3810i
-0.8880
-0.5199
-0.7576

The closed-loop frequency responses were obtained from the command *bode(as-l*cs,l,cs,ds)*, and the results show that the bandwidths were about 2 rad/sec and that the dc gain was 0 dB in all four loops.

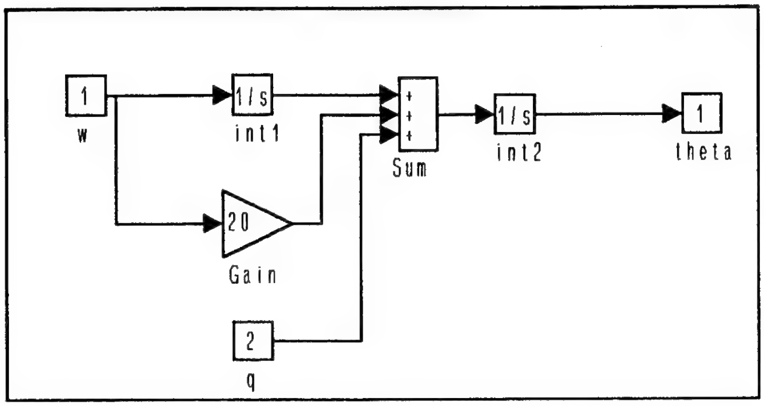
c. Kalman Filter

The eigenvalues of the Kalman filter matched those of the synthesis model and confirmed a properly functioning Kalman filter. The Kalman gains 'l' were saved to a *.mat* file and were later used by the filter as a part of the total system.

3. Angle Kalman Filter

The Euler angles Kalman filter was designed using the synthesis model in Figure 5.7. The model was linearized and verified.

Figure 5.7 Euler Synthesis Model



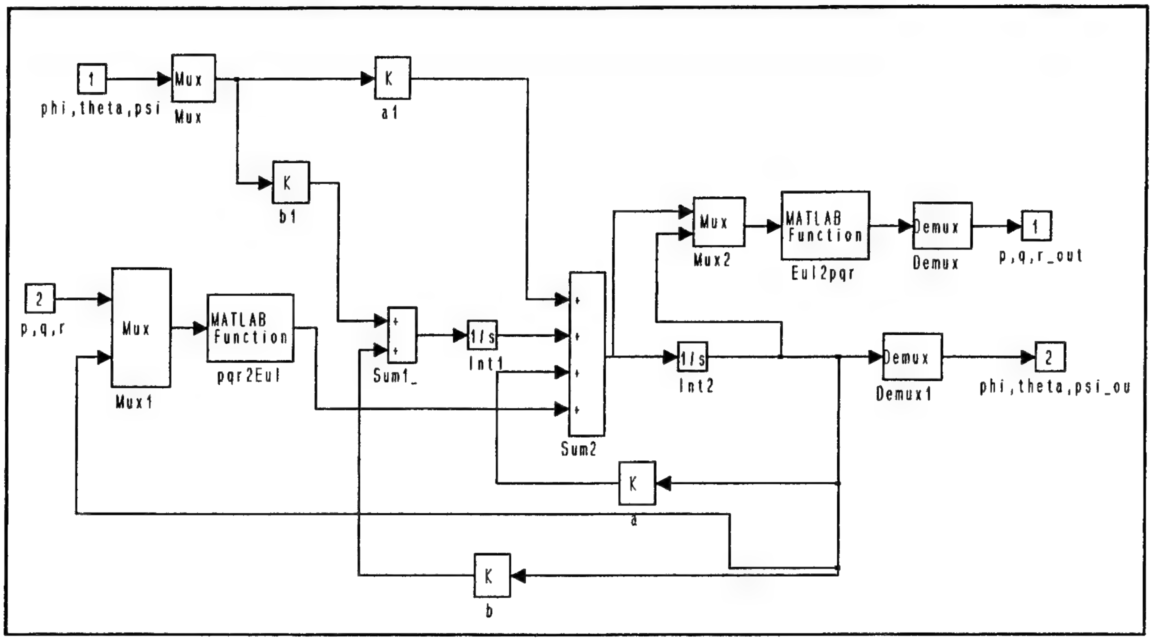
We chose a bandwidth of 2 radians/sec and designed the filter to achieve that goal. Initially, our selection of the zero location produced a large overshoot. Through trial and error, the synthesis gain of 20 produced the best results and yielded a zero at -0.05. When we completed the design, the Kalman gains were:

8.9941

0.4472

The final design is shown in Figure 5.8.

Figure 5.8 Euler Kalman Filter



4. EOM/Sensors/Kalman Filter Integrated System

Trim values were added to the incremental deflection inputs to the equations of motion for a trimmed flight. The system outputs were the errors (differences) between true and estimated position, Euler angles, and rotational velocities. The position Kalman filter initiated correction for four meter position errors within three seconds and stabilized them to within 0.1 meters at 20 seconds. The small error was due primarily to cross- axis sensitivity and decreased as the phugoid motion damped out.

The Euler and rotational velocity errors immediately corrected from a maximum of 0.0048 degrees to zero ± 0.001 degrees. As with the linear acceleration, this small error

was due primarily to cross-axis sensitivity in the rate gyros. However, as the phugoid motion damped, all angular rates tended to zero.

At frequencies below 0.4 Hz the filter used pseudoranges to determine position, and at frequencies above 0.5 Hz, the filter used inertial accelerations integrated twice. The integrated system response demonstrated very robust error corrections and precise position tracking.

D. CONTROL SYSTEM DESIGN

1. Requirements for the System

The requirements were to control the aircraft in the lateral and longitudinal directions. The design was for a cruise condition. We drove lateral velocity v (or equivalently sideslip) to zero in steady state to provide turn coordination.

Design Requirements

a. System is stable.

b. Steady state errors are zero.

c. Step response overshoot can not exceed 20%.

d. Step response rise time should not exceed 10 sec for u velocity, 4 sec for v velocity, 12 sec for Ψ command, and 12 sec for altitude command.

e. Gain and phase margins for elevator and thrust must be at least 6 dB and 45 degrees.

f. Elevator loop bandwidth should not exceed 20 rad/sec and thrust loop bandwidth should not exceed 5 rad/sec. Aileron loop bandwidth should not exceed 10 rad/sec, and rudder loop bandwidth should not exceed 15 rad/sec.

2. Open Loop Analysis

The A,B,C and D matrices were obtained from the EOM. Since the equations were of the form

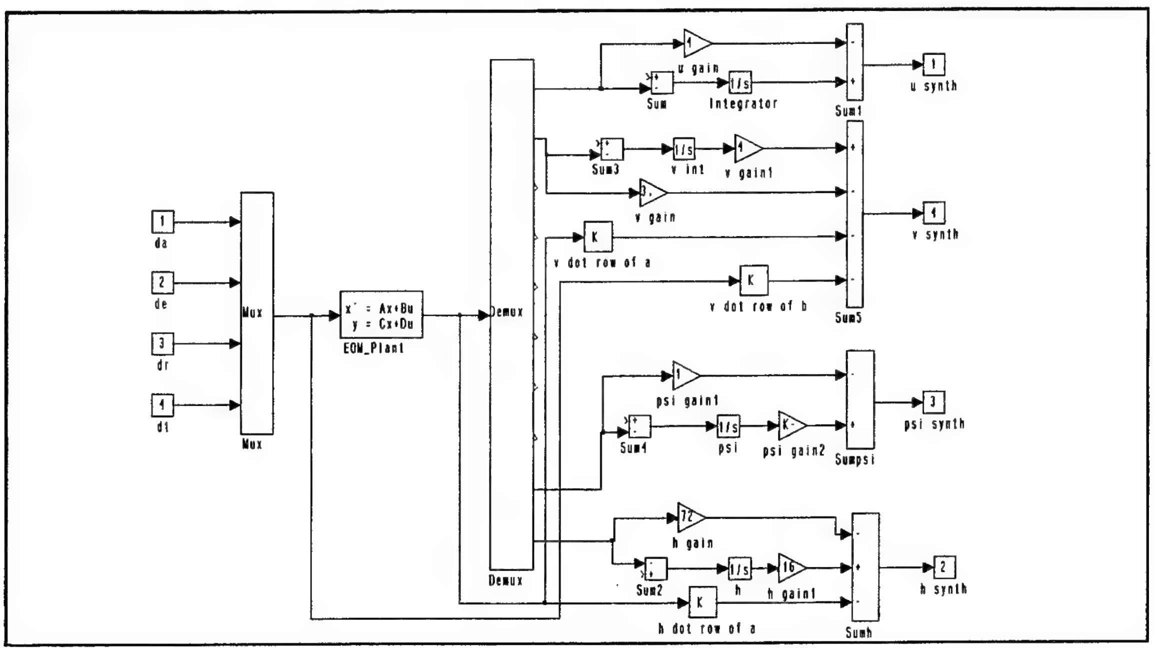
$$g=\begin{Bmatrix} \dot{x}=Ax+Bu \\ y=x \end{Bmatrix} \tag{5.14}$$

then

$$J(u)=\int^{t}(x^{T}Qx+u^{T}Ru)\,dt\geq 0,\ R>0 \tag{5.15}$$

A synthesis model was created as shown in Figure 5.9. This synthesis model was linearized to obtain new matrices.

Figure 5.9 Controller Synthesis Model



Using the algebraic Ricatti Equation C(s)=K, where $K = -R^{-1}B^TP$ for $P\geq 0$, $A^TP + PA - PB^TR^{-1}BP + Q = 0$ and having the synthesis model in the form

$$g_s = \begin{Bmatrix} \dot{x}_s = A_{sx_s} + B_{su} + B_1 w \\ z = C_s x_s + D_1 u \\ y = x_s \end{Bmatrix} \tag{5.16}$$

with $K = [K_p \ K_i]$, then

$$\begin{bmatrix} \delta_{e_0} \\ \delta_{a_0} \\ \delta_{r_o} \\ \delta t_o \end{bmatrix} = K(sI - A_s + B_{sK})^{-1} B_s \begin{bmatrix} \delta_{e_c} \\ \delta_{a_c} \\ \delta_{rc} \\ \delta t_c \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ t_{41} & t_{42} & t_{43} & t_{44} \end{bmatrix} \begin{bmatrix} \delta_{e_c} \\ \delta_{a_c} \\ \delta_{rc} \\ \delta t_c \end{bmatrix} \tag{5.17}$$

The control bandwidth is given by

$$t_{11} = \frac{\delta_{e_o}}{\delta_{e_c}}(s), \quad t_{22} = \frac{\delta_{a_o}}{\delta_{a_c}}(s), \quad t_{33} = \frac{\delta_{r_o}}{\delta_{r_c}}(s), \quad t$$

The off-diagonal terms show how much cross-coupling exists between control command and control inputs.

Similarly,

$$\begin{bmatrix} h \\ v \\ \psi \\ u \end{bmatrix} = C_s(sI - A_s + B_{sK})^{-1} B_1 \begin{bmatrix} h_c \\ v_c \\ \psi_c \\ u_c \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{bmatrix} \begin{bmatrix} h_c \\ v_c \\ \psi_c \\ u_c \end{bmatrix} \tag{5.18}$$

and here $\frac{h}{h_c}=s_{11}$, $\frac{v}{v_c}=s_{22}$, $\frac{\psi}{\psi_c}=s_{33}$ and $\frac{u}{u_c}=s_{44}$. The command loop bandwidth was determined by the bandwidth of s_{11}, s_{22}, s_{33}, and s_{44}.

3. Controller Design

The control and command loop bandwidths were determined through an iterative process where we let

$$R=\begin{bmatrix}\rho_e & 0 & 0 & 0\\ 0 & \rho_a & 0 & 0\\ 0 & 0 & \rho_r & 0\\ 0 & 0 & 0 & \rho_t\end{bmatrix} \tag{5.19}$$

$$Q=C_1^T\begin{bmatrix}\rho_h & 0 & 0 & 0\\ 0 & \rho_v & 0 & 0\\ 0 & 0 & \rho_\psi & 0\\ 0 & 0 & 0 & \rho u\end{bmatrix}C_1 \tag{5.20}$$

As ρ_e, ρ_a, ρ_r, $\rho_t\rightarrow$, bandwidth in t_{11}, t_{22} increased,

as ρ_e, ρ_a, ρ_r, $\rho_t{}^-$, bandwidth in t_{11}, t_{22} decreased,

as ρ_h, ρ_v, ρ_ψ, $\rho_u\rightarrow$, bandwidth in s_{11}, s_{22} increased, and

as ρ_h, ρ_v, ρ_ψ, $\rho_u\rightarrow 0$, bandwidth in s_{11}, s_{22} decreased.

Initially, we set

$$\begin{aligned}R&=I\\ Q&=C_1^T I C_1\end{aligned} \tag{5.21}$$

Then we computed

$$K=R^{-1}B^{T}P \tag{5.22}$$

If the bandwidths were too small or too large, ρ_h, ρ_v, ρ_ψ, ρ_u or ρ_e, ρ_a, ρ_r, ρ_t were modified. The final values used for the controller were computed to be:

$$R=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1000 & 0 & 0\\ 0 & 0 & 50 & 0\\ 0 & 0 & 0 & 10\end{bmatrix} \tag{5.23}$$

$$Q=C_1^T\begin{bmatrix}.01 & 0 & 0 & 0\\ 0 & .001 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & .005\end{bmatrix}C_1 \tag{5.24}$$

Once the values for K were found, the closed loop controller was designed. The optimum K values were as follows:

Ki =

0.0000	-0.0030	-1.1069	0.0000
-0.0395	0.0000	0.0000	-0.0042
0.0000	-0.0550	1.1903	0.0000
-0.0186	0.0000	0.0000	0.0009

Kp =

0.0000	0.0046	0.0000	0.2621	0.0000	0.0350	0.1953
0.0000	3.0256	0.0000				
0.1546	0.0000	0.0279	0.0000	-1.1580	0.0000	0.0000
0.0000	3.0256	0.0000				
0.0000	0.0416	0.0000	0.4557	0.0000	-11.2566	0.4505
0.0000	-1.8829	0.0000				
0.0842	0.0000	-0.0048	0.0000	-0.0063	0.0000	0.0000
5.3970	0.0000	-0.0049				

The Bode plots for the open and closed loop controller are shown in Figure 5.10. The aileron controller had a 5db sensitivity increase at 0.19 rad/s and decreased within the bandwidth of approximately 2 rad/s. The elevator controller had a 2db sensitivity increase at 1.0 rad/s and decreased within the bandwidth of less than 2 rad/s. The rudder controller had a small 1db sensitivity increase at 5 rad/s and decreased within the bandwidth of just over 1 rad/s. All four controllers had an infinity gain margin and a minimum phase margin of 30 degrees, both within the design requirements of 6db and 45 degrees.

The velocity, altitude and Psi step responses are shown in Figure 5.11. The velocity components, u and v, and the altitude command step responses damped at 8, 1.5, and 8 seconds, within the design requirements of 10, 4, and 12 seconds, respectively. The Psi command step response was underdamped with a 10% overshoot at 6 seconds and damped at 11 seconds, within the design requirements of 20% overshoot and a 12 second rise time.

Figure 5.10 Aileron and Elevator Bode Plots

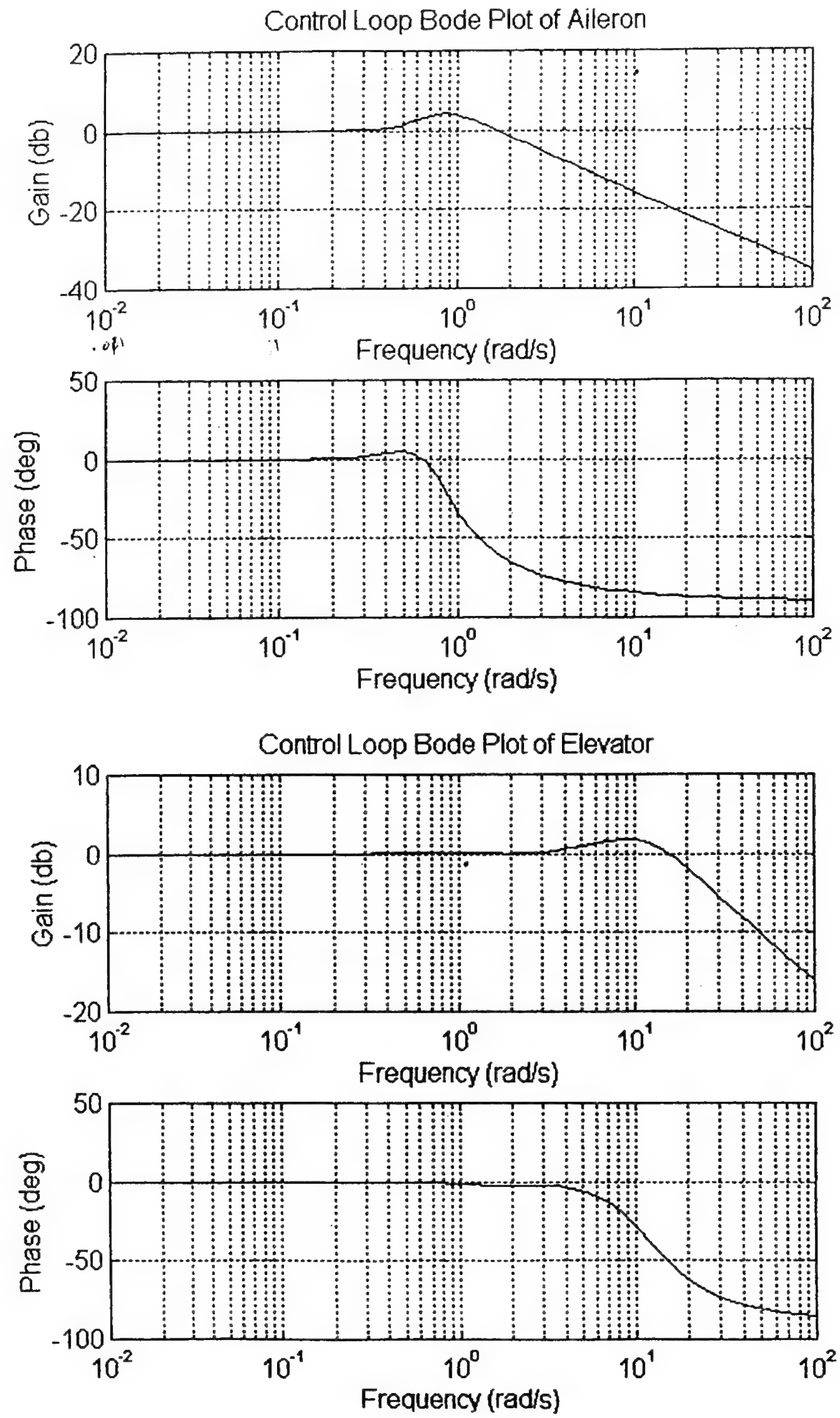


Figure 5.10 (cont'd) Rudder and Thrust Bode Plots

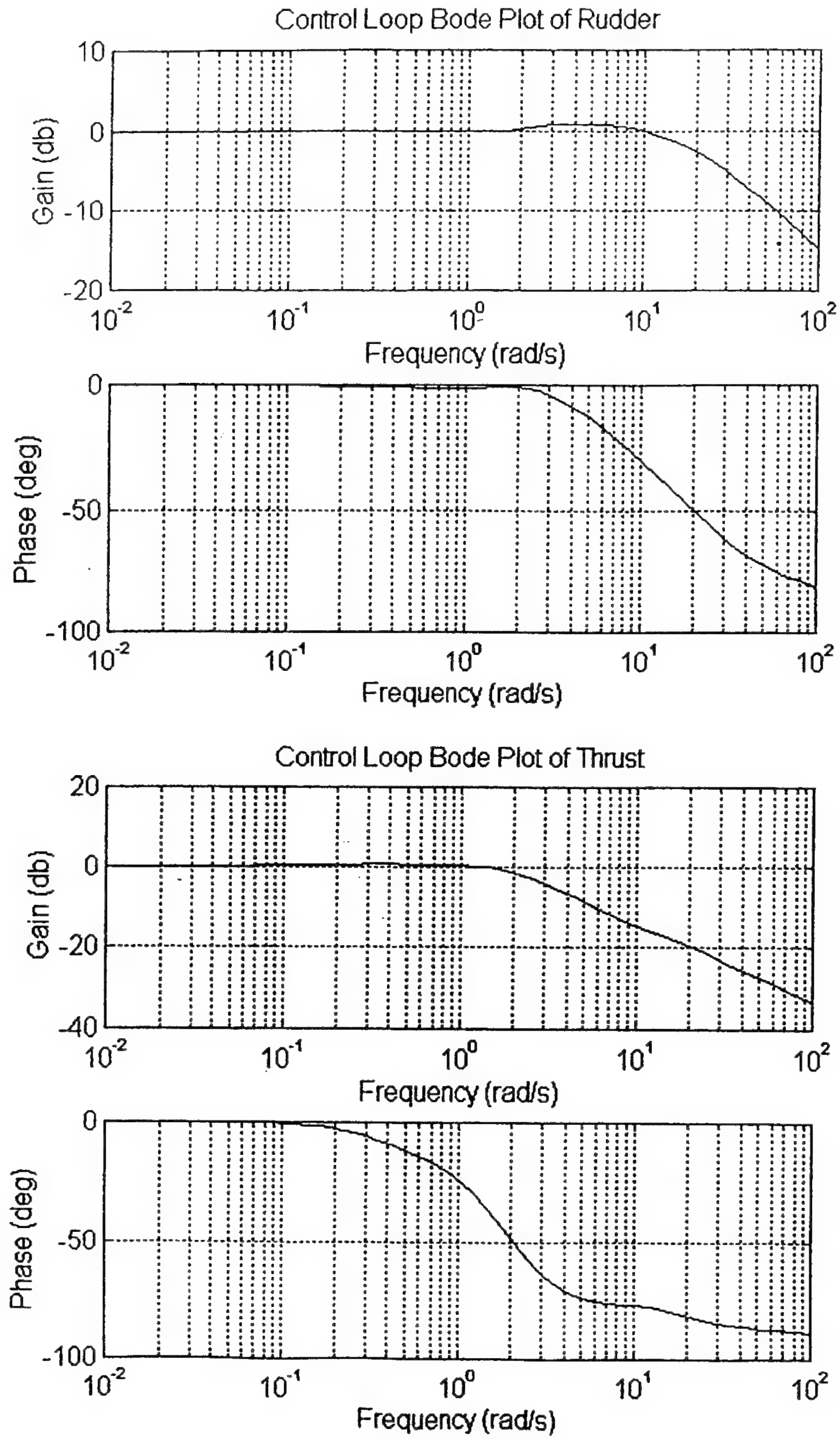


Figure 5.11 Velocity Step Response

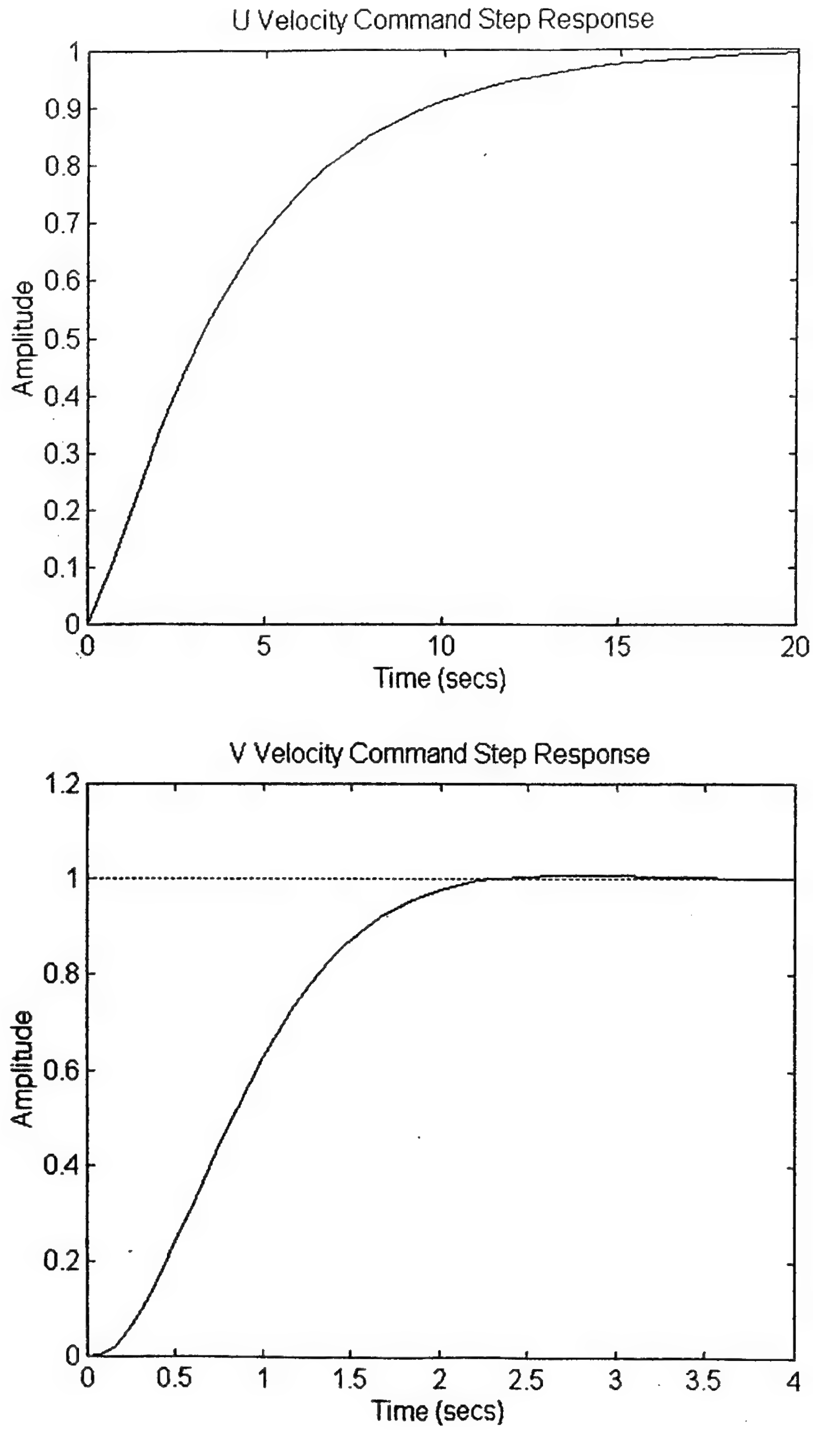
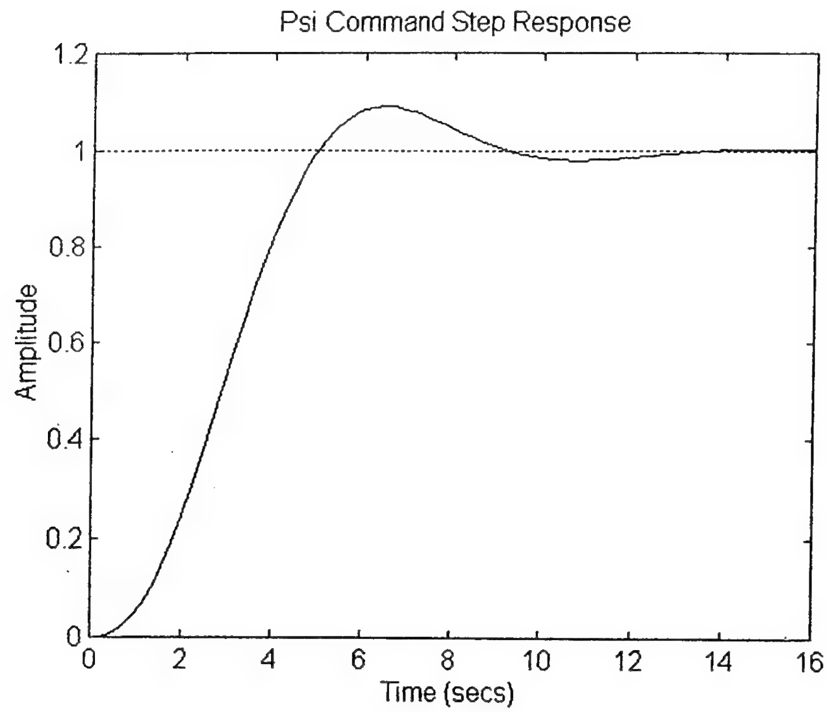
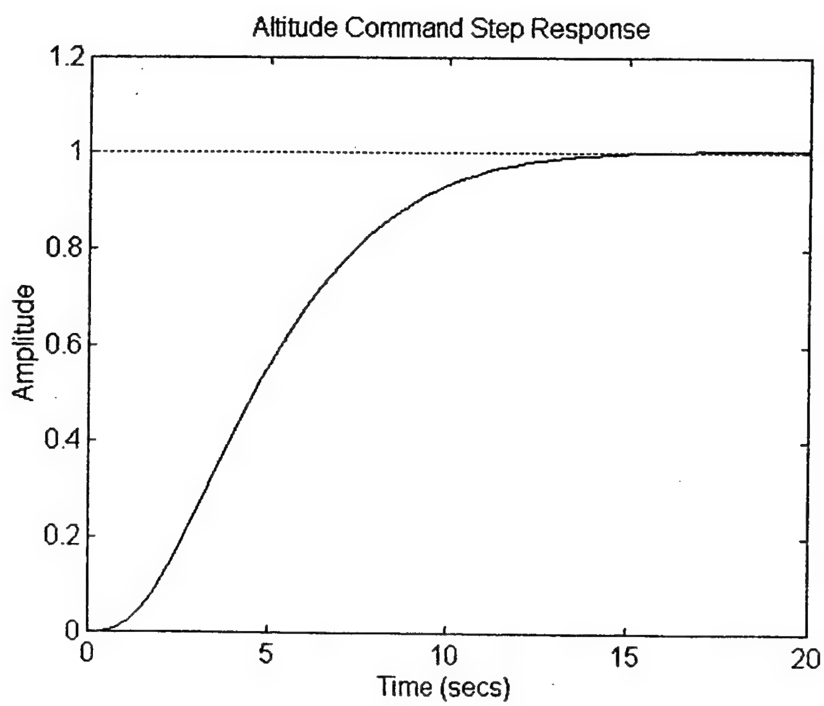


Figure 5.11 (cont'd) Psi and Altitude Step Response



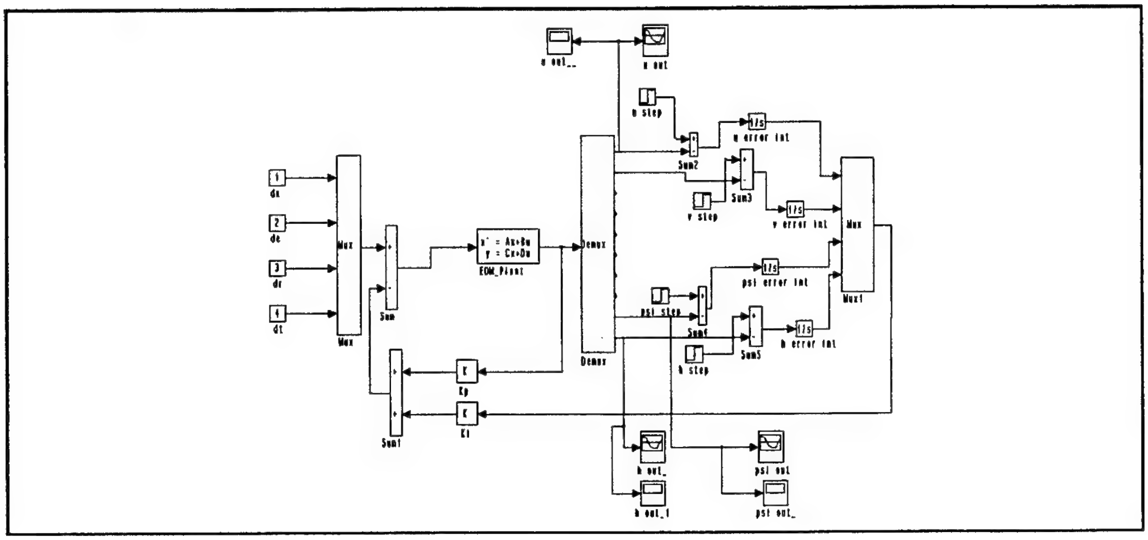


4. Closed Loop Analysis

a. *Linear Plant*

The linear controller is shown in Figure 5.12 with Ki and Kp values as determined from above. This was linearized to verify the eigenvalues.

Figure 5.12 Linear Controller



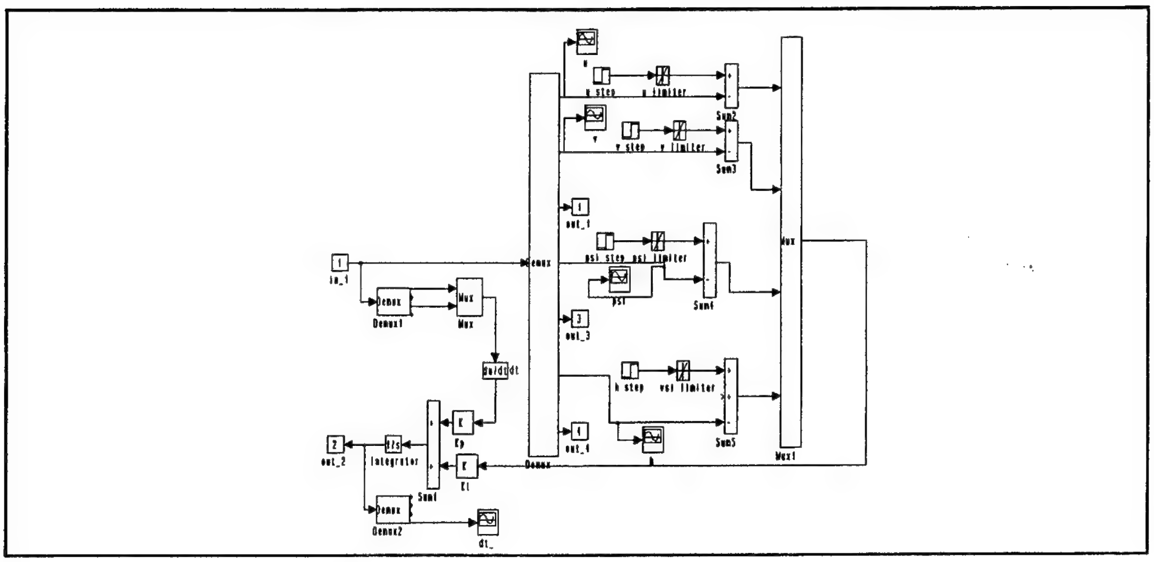
b. *Nonlinear Plant (EOM)*

The transmission zeros for the nonlinear plan was the null set as expected. An identical comparison to the fourth decimal place of the eigenvalues for the linear and nonlinear controller is given in Table 5.3. The nonlinear controller is shown in Figure 5.13.

Table 5.3 Eigenvalues

Linear Plant	Nonlinear Plant
-0.25	-0.25
-0.3484 + 0.7005i	-0.3484 + 0.7005i
-0.3484 - 0.7005i	-0.3484 - 0.7005i
-0.3547 + 0.1742i	-0.3547 + 0.1742i
-0.3547 - 0.1742i	-0.3547 - 0.1742i
-0.7201 + 0.2166i	-0.7201 + 0.2166i
-0.7201 - 0.2166i	-0.7201 - 0.2166i
-1.4885 + 1.1872i	-1.4885 + 1.1872i
-1.4885 - 1.1872i	-1.4885 - 1.1872i
-1.5782 + 1.2201i	-1.5782 + 1.2201i
-1.5782 - 1.2201i	-1.5782 - 1.2201i
-7.8986 + 8.1216i	-7.8986 + 8.1216i
-7.8986 - 8.1216i	-7.8986 - 8.1216i
-15.8	-15.8

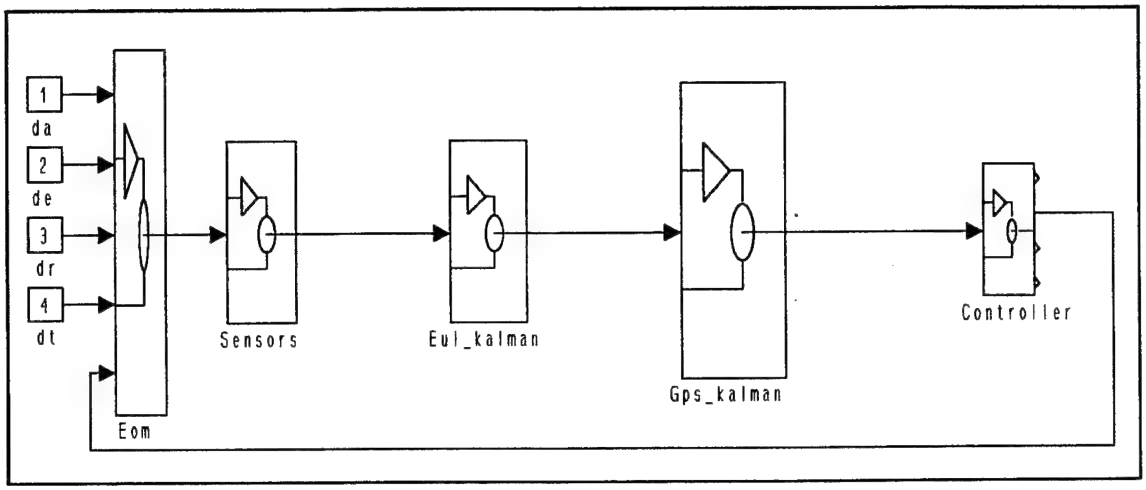
Figure 5.13 Nonlinear Controller



E. INTEGRATION OF ALL SYSTEMS

The completely integrated closed loop system is shown in Figure 5.14.

Figure 5.14 Total Intergrated System



The error plots are given in Figures 5.15 to 5.17. The XYZ position errors were small with average errors of 0.2, 0.07, and 0.13 feet respectively. The UVW velocity and $A_xA_yA_z$ acceleration errors were simular with less than 0.5 feet per second (feet per second squared) where U and A_x showed less than 0.1 deviation about zero while V, A_y, W, and A_z deviations were rapid 0.4 pertibations about zero. Errors and noise overshadowed the responses on the plots small scale, but trends remained evident. The integrated system was stable about the trim point with small pertibations in three axis.

Figure 5.15 Position Error in X, Y and Z

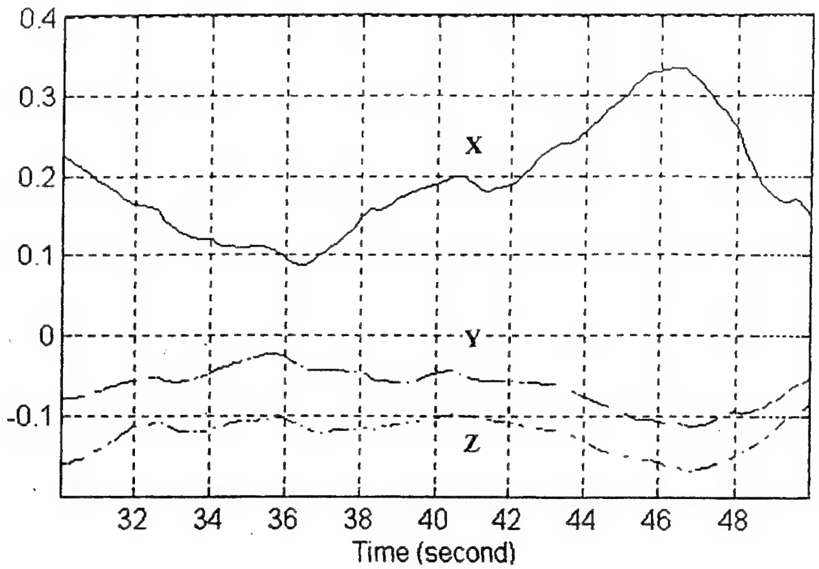


Figure 5.16 Velocity Errors U, V and W

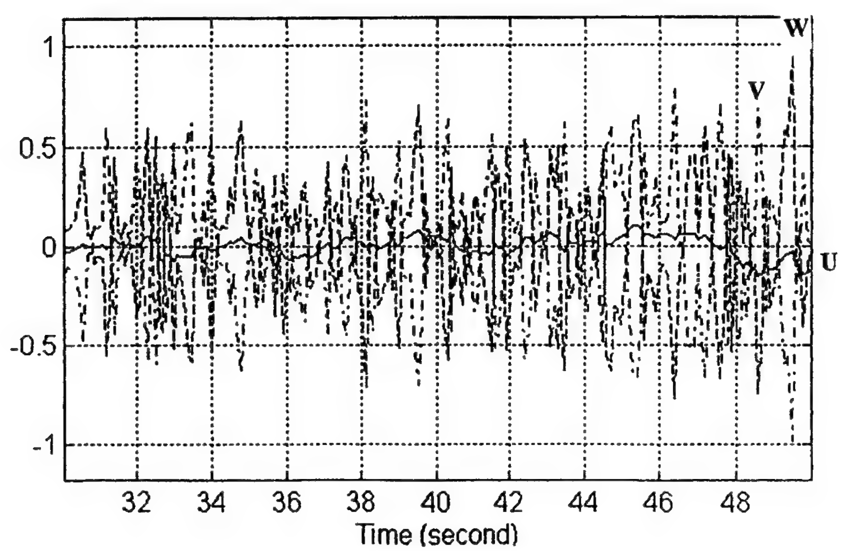
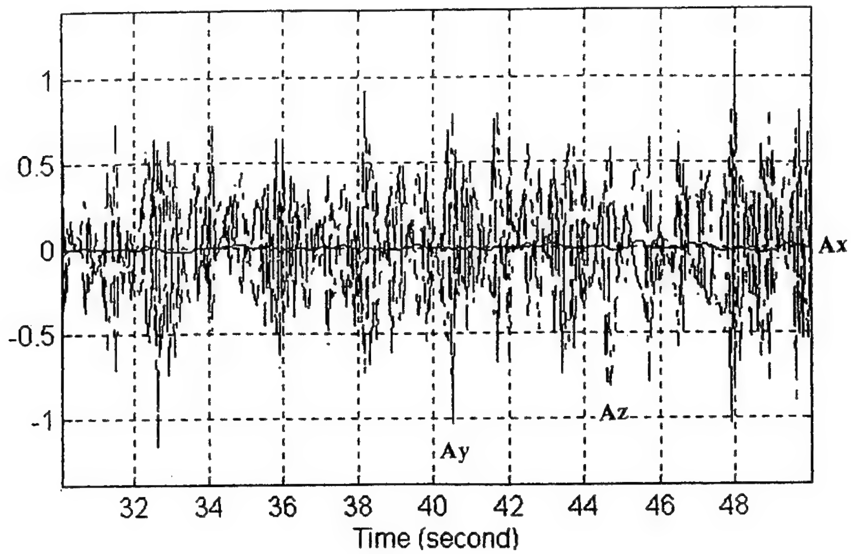


Figure 5.17 Acceleration Errors A_x, A_y, and A_z



F. SUMMARY

This design of a INS/GPS navigation/control system successfully implemented a nonlinear closed-loop integrated system (IGS). The navigation and control IGS stabilized the aircraft at the trim point developed and controlled velocity and altitude. This validated model now can be easily adapted for wind axis, full control in turn rate, heading, yaw rate, sideslip, rate of descent, and 3-D navigation. These modifications can be taylored to simulate the post launch flight of the JSOW glide weapon.

VI. CONCLUSIONS

The NPS Draft for the Concept for Operational Employment (ideas) is the foundation document from which the Functional Requirements (hardware), structural, and aerodynamic design work will progress. The 'conops' working copy has been forwarded to PMA-201E4 for review and will be disseminated to the Warrior Product Team (WPT). The WPT members include key field and office acquisition managers, aviators, and represent the USN, USMC, and the USAF. They will review and critique the concepts presented to make sure that their type aircraft, mission specifics, and interoperability issues are satisfied.

The NPS draft for the Functional Requirements will continue to be revised. Chapter III is an initial draft that was written in parallel to a more indepth functional study (thesis) being conducted by LT Formet. He will incorporate Chapter III into his study to create a single Functional Requirements Document. As with the conops document, the Functional Requirements will be forwarded to PMA-201E4.

The feasibility study for a multi-weapon CATM has merit. Aviators entering the 21st century can justifiably expect a multi-weapon training system that provides exact simulation, optimizes training per flight and maintenance hour, and has growth to accommodate future weapon simulations. A complete component interface analysis would be an excellent thesis topic for an Avionics, Weapon Systems, Computer Science or Electrical Engineering student.

The SIMULINK Dynamic Systems Design simulation will continue into the next academic quarter with CDR(S) Wagner and LT Klein further developing the equations of motion and the feedback controllers as they add wind axis, turn rates, lead turns and 3-D waypoint navigation. The following quarter, CDR(S) Wagner will incorporate Designers Workbench virtual prototyping software and CATM flight director commands.

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Notes From Unitary CATM Working Meeting, NAWC China Lake, 24Oct95.

Notes From Unitary CATM Warrior Product Team Meeting, Texas Instruments, Dallas Texas, 30-31Jan96.

APPENDIX

MATLAB programs for JSOW INS/GPS systems preliminary design.

```
function [dlambda] = deuler (vec1)

% this subroutine computes time  derivatives of the Euler
% angles given  a/c angular velocity and Euler angles
% the input is 6x1 vector = [ p q r roll pitch yaw]'
% the output is d/dt [roll pitch yaw]'
% function [dlambda] = deuler (vec)

p = vec1(1);
q = vec1(2);
r = vec1(3);
roll = vec1(4);
pitch = vec1(5);
yaw = vec1(6);

droll = p + sin(roll)*tan(pitch)*q + cos(roll)*tan(pitch)*r;
dpitch =  cos(roll)*q - sin(roll)*r;
dyaw =  (sin(roll)*q + cos(roll)*r)*inv(cos(pitch));
dlambda = [droll;dpitch;dyaw];
```

```
function [Pdot] = dposit(vstate)

%  This function computes time derivative of the vehicle's
%  position given vbob and euler angles.  The input is a 6x1
%  vector [u;v;w;phi;theta;psi].  The output is a 3x1 vector
%  d/dt [x;y;z].
```

```
u=vstate(1);
v=vstate(2);
w=vstate(3);
phi=vstate(7);
theta=vstate(8);
psi=vstate(9);

Pdot=Rb2u(vstate)*[u;v;w];
```

```
function wb = eul2pqr(vec)

% This function computes the aircraft angular velocities
% (p,q,r)given the time derivatives of the Euler angles
% (lambda dot) and Euler angles.
% The input is a 6x1 vector:  [droll dpitch dyaw roll pitch
% yaw]'. The output is a 3x1 vector:  [p q r]'

droll=vec(1);
dpitch=vec(2);
dyaw=vec(3);
roll=vec(4);
pitch=vec(5);
yaw=vec(6);

p = droll - sin(pitch)*dyaw;
q = cos(roll)*dpitch + cos(pitch)*sin(roll)*dyaw;
r = -sin(roll)*dpitch + cos(pitch)*cos(roll)*dyaw;

wb=[p q r]';
```

```
function rho=exact(x)

% Given receiver position and satellite positions input from
% .mat variable s5 this function computes the exact range
% and elevation angle (radians) from the aircraft to all the
% satellites. It then sorts the elevation order of all s5
% satellites in order of the highest elevation to the lowest
% then reorders the satellite distance to match. Only the
% satellite ranges (rho) with the four highest angles are
% forwarded from the program.
% All distances are meters.

%       satnum          number of satellites
%       ePsat           satellite position in {e}
%       uPsatu          satellite position in {u}, referenced
%                      to {u}
%       uPsatb          satellite position in {u}, referenced
%                      to {b}
%       ePbo            body position in {e}
%       uPbo            body position in {u}
%       ePou            tangent plane in {e}
%       Rhob            distance from body to satellite
%       Teu             transfer matrix from {e} to {u}
%       Tue             transfer matrix from {u} to {e}
%       Rub             rotation matrix from {UEN} to {NED}
%       altnorm         satellite normalized altitude vector
%                      in {b}

satnum=(length(x)-3)/3;
ePsat=zeros(satnum,3);

% define receiver position matrix
uPbo=x(1:3);            % {NED}
```

```
% ***later will need to define tanget plane position matrix
%    as Tx,Ty,Tz
%    referenced to ECEF or as lat/long/alt. Suggest read
%    from .mat file ***

% define satellite position matrix
for j=1:satnum;
ePsat(j,:)=x(3*j+1:3*(j+1))';        % {UEN}
end

% define semi-major and semi-minor ellipsoid axes
a=6378137;           % meters
b=6356752.3142;

% define flattening factor (f) and eccentricity squared (ee)
f=(a-b)/a;
ee=(2-f)*f;

% convert tangent plane position to geodetic lat, long, &
% height
% for now lat=long=0
lambda=0;       % atan(Ty/Tx);
phi=0;          % atan(inv(1-ee)*Tz/sqrt(Tx^2+Ty^2));

% calc N & geodetic height h
N=a/sqrt(1-(ee*sin(phi))^2);
h=0;             %sqrt(Tx^2+Ty^2)/cos(phi)-N;

% define tangent plane transfer matrix from {e} to {u}
Teu=[cos(phi)*cos(lambda) cos(phi)*sin(lambda) sin(phi);
    -sin(lambda)              cos(lambda)             0;
    -sin(phi)*cos(lambda)   -sin(phi)*sin(lambda)
cos(phi)];
Tue=inv(Teu);
```

```
% rotate tangent plane from {UEN} to {NED} to match aircraft
% axis
 Rub=[0  0  1;
      0  1  0;
     -1  0  0];

% define vectors and solve for satellite range 'rho'
ePbo=Tue*inv(Rub)*uPbo;                         % {UEN}

ePou=[(N+h)*cos(phi)*cos(lambda);               % {UEN}
      (N+h)*cos(phi)*sin(lambda);
       N*sin(phi)              ];

for j=1:satnum;
  Rhob(j)=norm(ePsat(j,:)'-ePou-ePbo);          % {UEN}
  uPsatu=Teu*(ePsat(j,:)'-ePou);                % {UEN}
  uPsatb=uPsatu-inv(Rub)*uPbo;                  % {UEN}

  % check_Rhob=norm(uPsatb)

% normalize the altitude difference vector to a unit vector

altnorm(j)=uPsatb(1)/real(sqrt(uPsatb(1)^2+uPsatb(2)^2+uPsat
b(3)^2));

end

% the altitudes are sorted from high to low and correspond
% ing
% positions are found and matched to sequence

srtd=flipud(sort(altnorm)');

s=zeros(4,1);
```

```
s(1)=Rhob(find(altnorm==srtd(1)));
s(2)=Rhob(find(altnorm==srtd(2)));
s(3)=Rhob(find(altnorm==srtd(3)));
s(4)=Rhob(find(altnorm==srtd(4)));


% the output is receiver position and the positions of the
% four highest satellites

rho=s;
```

```
function g = grav_tan(r)

% This function computes the gravity vector (meters/sec^2)
% in the tangent plane r is the vector of the vehicle's
% position in tangent plane

R0 = 6.4e6;
mu = 9.81*R0^2;
R = (r(1)^2 + r(2)^2 + (r(3) + R0)^2)^.5;
gx = -(mu/R^3)*r(1);
gy = -(mu/R^3)*r(2);
gz = -(r(3) + R0)*mu/R^3;

g = [gx; gy; gz];
```

```
function accel=main(vstate)

%  This function calculates the linear and angular accelera-
%  tions for the equations of motion for a vehicle.
```

```
% The states are:
%   u = x velocity component in {b}
%   v = y velocity component in {b}
%   w = z velocity component in {b}
%   p = roll rate in {b}
%   q = pitch rate in {b}
%   r = yaw rate in {b}
%   phi = euler angle about x components
%   theta = euler angle about y components
%   psi = euler angle about z components
%   x = x position component of vehicle in {u}
%   y = y position component of vehicle in {u}
%   z = z position component of vehicle in {u}
% Note:  position components are calculated by another func
% tion and are not used in main.
% The control inputs are:
%   da = incremental aileron deflection
%   de = incremental elevator deflection
%   dr = incremental rudder deflection
%   dt = incremental change in thrust.  For cruise dt = 1.

% Define states with respect to the input vector:
u=vstate(1);
v=vstate(2);
w=vstate(3);
p=vstate(4);
q=vstate(5);
r=vstate(6);
phi=vstate(7);
theta=vstate(8);
psi=vstate(9);

% Define the control inputs with respect to the input vector:
da=vstate(10);
```

```
de=vstate(11);
dr=vstate(12);
dt=vstate(13);
%  for cruise,
%dt = 1;
d=[da;de;dr;dt];

%  Ititialize data used in main:
[Vt0,h0,alpha0,beta0,S,b,cbar,rho,CTx1,g,mass,Cf1,Cfd,Cfx,Cf
xdot,Ib] = initial_data;

%  Calculate u0,v0,w0:
V0body=Rw2b(alpha0,beta0)*[Vt0;0;0];
u0=V0body(1);
v0=V0body(2);
w0=V0body(3);

%  Calculate aerodynamic terms:
Vt=sqrt(u^2 + v^2 + w^2);
qbar=(0.5*rho*Vt^2);

%  Calculate alpha and beta:
alpha=asin(w/Vt);
beta=asin(v/Vt);

%  Calculate M1, M2, Sbar:
M1=(1/Vt)*diag([1 1 1 b/2 cbar/2 b/2]);
M2=diag([0 b/(2*Vt*Vt) cbar/(2*Vt*Vt) 0 0 0]);
Sbar=diag([-S S -S S*b S*cbar S*b]);

%  Calculate chi:
%Cfxdot = getcfxd;
A=[eye(3)/mass zeros(3);zeros(3) inv(Ib)];
rot=[Rw2b(alpha,beta) zeros(3);zeros(3) Rw2b(alpha,beta)];
```

```
chi=eye(6)-(A*rot*qbar*Sbar*Cfxdot*M2);

%  Calculate gravity component in {b} given gravity in {u}:
G = [inv(Rb2u(vstate));zeros(3)]*[0;0;g]*mass;

%  Calculate forces and moments given stability and control
derivatives:
vec = [u-u0;v;w-w0;p;q;r];
H= rot*qbar*Sbar*(Cf1+Cfx*M1*vec+Cfd*d);

%  Calculate thrust:
T0=CTx1*qbar*S;
Thrust = [T0;zeros(5,1)]*dt;

%  Cross products:
vbob=vstate(1:3);
omega=vstate(4:6);
vdot=-crpr(omega,vbob);
omegadot = -inv(Ib)*crpr(omega,Ib*omega);

%  Final equation.  These are linear and angular accelera
%  tions:

accel = inv(chi) * ([vdot;omegadot] +A*(G+Thrust+H));

-------------------------------------------------------------

function xout = Rb2u1(vstate)

%  This function calculates rotation matrix from body {b} to
%  inertial {u} axis.  Inputs are euler angles phi, theta,
%  and psi and bA.  Used in sensors_s.

phi = vstate(1);
```

```
theta = vstate(2);
psi = vstate(3);
bAx= vstate(4);
bAy= vstate(5);
bAz= vstate(6);

Rpsi = [cos(psi) -sin(psi) 0;sin(psi) cos(psi) 0;0 0 1];
Rtheta = [cos(theta) 0 sin(theta); 0 1 0; -sin(theta) 0
cos(theta)];
Rphi =  [1 0 0; 0 cos(phi) -sin(phi); 0 sin(phi) cos(phi)];

xout =[Rpsi*Rtheta*Rphi]*[bAx;bAy;bAz];
```

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